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論文審査委員	主　査　教　授　須藤 滋 教　授　俵 博之 教　授　濵田 泰司 教　授　加藤　義章（京都大学） 助教授　佐藤　國憲（核融合科学研究所）

論文内容の要旨

Three new classes of reflection grating spectrometer invented by the author are reviewed. The optical designs were devised for use at grazing incidence and have the following features in common: 1) a stationary ("fixed") entrance slit, 2) a fixed exit slit or normal incidence focal surface, 3) spectral images absent of low order aberrations, 4) only simple surface shapes (plane or sphere), 5) scanning motion(s) of only a single optic and 6) a small number of optical surfaces. These capabilities are crucial for soft x-ray and extreme ultraviolet spectroscopy in astrophysics, in the diagnostics of inertially and magnetically confined plasmas and in the study of material properties such as in surface science and optical component characterization. The geometrical insight which led to each design is presented and the detailed optical properties are derived from first principles and further verified using numerical raytracing computations. Experimental results are reported to demonstrate the practical viability and significance of each spectrometer design in several fields of scientific research.

The first design class consists of a plane (or ultra-large radius) grating surface having groove spacings which vary continuously across its width and operating in converging light (a virtual object). This varied line-space (or "VLS") plane grating design originated from the constraints imposed by an extreme ultraviolet space astronomy satellite, in which a high efficiency, slitless and stigmatic spectrum was required onto a small normal incidence detector within a short physical envelope. This mission (EUVE) was successfully deployed by NASA and provided the first high resolution ($\lambda/\Delta\lambda \sim 300$) spectra of extra-solar objects in the 70-760 Angstrom region using three grating channels in the spectrograph. A high resolution array of such plane gratings is now under construction for use on a future soft x-ray astronomy mission (XMM).

Improvements to this basic plane VLS grating design resulted in a versatile laboratory instrument. The High Resolution Erect Field Spectrometer (HIREFS) provides for the scan of wavelength between fixed slits by a pure rotation of the grating, without compromise of spectral or spatial resolution. The author designed, built and calibrated fifteen such systems operating from ~ 6 Angstroms to ~ 1500 Angstroms. These spectrographs and monochromators are currently in use at ~ 10 laboratories worldwide in a variety of applications. These include diagnosis of z-pinch plasmas, extreme ultraviolet lasers and femtosecond laser-produced gas harmonics, long beam calibration of astronomical telescopes, multilayer optics characterization, non-linear material interactions, soft x-ray CCD development and x-ray atomic fine structure (XAFS). Using 10 micron slits, spectral resolving powers of 1,500 to 35,000 (depending upon the grating focal length) have been obtained combined with stigmatic image spatial resolutions of approximately 5 arcseconds in the non-dispersive direction. Soft x-ray efficiencies of ~ 5-10% are obtained for the imaging spectrometer comprised of three

reflections. Due to the plane grating surface and the minimal amount of variation in the groove spacing, the uniformity of intensity is good in the meridional direction of the output aperture.

A second class of spectrometer was conceived to enable higher throughput primarily as a monochromator. The In-Focus Monochromator (IFM) is comprised of a self-focusing VLS grating and fixed entrance and exit slits. To scan wavelength the grating is rotated, and the resulting aberrations are corrected by a small translation along its surface. Due to the varied spacing, such translation results in a change to the groove density and all its derivatives at the fixed optical axis. This provides enough degrees of freedom to entirely remove first order defocusing, make second order aberrations negligible and minimize spherical aberration. In this way, a single optical element provides in-focus spectral images at all wavelengths scanned between stationary slits. This combination of desirable properties in the IFM is possessed by no other grazing incidence monochromator. The fundamental novelty of this new condition of grating focusing may be appreciated from the fact that the surface translation would have no such effect in the case of a classical (equally-spaced) grating.

The author designed a compact model of the IFM and has built and calibrated six such systems now in use for CCD characterization, optics and detector calibration, laser-plasma diagnostics and photo-electron spectroscopy. Using 10 micron slits, resolving powers of ~ 500 are obtained in the 6-400 Angstrom region at a typical absolute efficiency of 25%. One of these six IFM systems was a stigmatic version which delivers high brightness point-like monochromatic images to a target surface in ultra-high vacuum. The system has a solid collection angle of 30 mrad x 3.4 mrad and provides maximum reflection efficiency in the extreme ultraviolet by use of rhodium coatings on the mirror surfaces.

In addition to the applications reported here, synchrotron radiation facilities have also built the above types of monochromator using the author's published inventions of a plane varied-space grating in a converging beam or a rotating and translating self-focusing varied-space grating. These facilities have variously renamed these monochromators (e.g. "VLS Monk-Gillieson", "HERMON", etc.).

The third class of spectrometer was motivated by the desire for a high energy grating monochromator which maintains a fixed aperture output beam over a broad range in scanned wavelength and does not require high accuracy for the mechanism which scans wavelength. When operated at a small graze angle (e.g. 1°), conventional rotation of a reflection grating about its central groove results in a diffracted wavelength which is very sensitive to the angle of rotation. Such rotation also produces a large change in the numerical aperture of the diffracted beam as a function of wavelength and a defocusing of the image. However, if a grating is rotated about its surface normal, then the beam geometry and focusing conditions remain essentially unchanged at grazing incidence, while the incident photon views an effectively increased groove spacing. The Surface Normal Rotation (SNR) monochromator enables, for example, the use of a simple

concave grating with equidistant grooves operating on the Rowland circle. The surface normal rotation geometry also provides for a broader curve of diffraction efficiency and thus a wider range in wavelength which can be efficiently covered by a single grating. In addition, the accuracy required of the rotation scan is extremely low, due to the cosine dependence of the wavelength upon the rotation angle. Finally, the use of equally-spaced grooves and a single optical surface minimize the variation of efficiency across the diffracted output aperture.

Theoretical calculations and soft x-ray experimental results are presented for two single-element versions of the SNR monochromator designed for application to the testing of astronomical telescopes (ASTRO-D and XMM). The first of these reports the highest photon energy (4 keV) yet obtained for a reflection grating. The second design maintains a resolving power of approximately 1,000 over the soft x-ray region from 10 to 50 Angstroms, by providing a tilt rotation of the grating simultaneous with the surface normal rotation. It is interesting to note that the SNR technique exhibits the unconventional property that the performance improves as the graze angle is reduced. Being the only known case in the history of gratings where the optical aberrations are smaller at grazing incidence than at normal incidence clearly illustrates that such a geometrical solution would not have evolved from the usual method of revising classical designs.

Recently there has been a growth in the use of increasingly sophisticated and immovable sources of soft x-ray radiation, including magnetically confined fusion plasmas, inertially confined plasmas driven by lasers or other pulsed sources and charged particle accelerators. This has been accompanied by the development of new and essentially immovable soft x-ray detectors such as streak cameras, charge-coupled devices (CCDs) and x-ray calorimeters. Adaptations of the classical Rowland circle and plane grating geometries are found inadequate to couple efficiently to such sources and detectors. Future advances in short wavelength spectroscopy must be made with equally advanced spectrometer geometries which employ stationary slits yet maintain high spectral and spatial resolutions.

The high efficiency resulting from use of a minimum number of grazing incidence reflections, the high spectral resolution provided by varied groove spacings and novel yet simple scanning motions of accurate plane or spherical optical surfaces, and the high spatial resolution enabled by stigmatic geometries, make the spectrometer systems presented in this work useful in many fields of current research. Of particular interest is the application of such new geometries to the study of the spatial and temporal inhomogeneities in plasmas. A varied line-space monochromator can provide high spectral resolution and two-dimensional spatial imaging of extended plasmas at high throughput by use of only two optical elements.

論文の審査結果の要旨

軟X線から真空紫外域の斜入射分光器において、（a）入・出射スリットを固定し、（b）低次のオーダーの収差を取り除き、（c）システム中一つだけの光学素子を駆動するのみ、という特徴を持つ実用的な３種類の斜入射型分光器を考案し、レイ・トレーシングを含め理論的に解析を行うとともに、実際に製作し、性能を実験的に実証した。それらの分光器は次の３つに大別される。（１）溝間隔が連続的に変化する平面回折格子（VLS）を用いた分光器を考案・実用化し、これを衛星搭載用望遠鏡の分光計測器として３枚のグレーティング装着により 7 - 76 nm の領域を高波長分解能（300）を以て観測できるようにした。また、平面VLS回折格子を実験室用分光器として回折格子の回転機能を付加し高波長分解能を実現（1500 - 35000）しつつ使いやすいものにした。（２）凹面状VLS回折格子を用いて、入・出射スリットを固定しておき、回折格子のみを平進移動及び回転させることにより、波長スキャンができるようにし、分解能500程度で 0.6 - 40 nm 領域をカバーしている。（３）回折格子面に垂直な軸の周りに格子を回転させることにより、入・出射スリットを固定したまま、斜入射分光器において波長スキャンができるようにした。斜入射角が１度程度の浅い構成となる場合に有効であり、比較的短波長への適用時に有利となる。この方式により、斜入射分光器がコンパクトになり、且つ取り扱いを容易にした。

これらの分光器は実験室での観測の他、既に多くの分野、例えばNASAの太陽系外観測などで多くの成果を挙げている。

分光器の技術は一般的には既に確立されたかの感があったが、博士論文提出者の新しい工夫により設計された分光器が最先端研究分野で現在も広く使われていることを見ても、独創的且つ実用的であることが理解される。

また、基礎原理から出発して本論文の研究成果に至るまでを丁寧に記述しており、優れた論文となっている。審査手続きの厳正な学術雑誌に第一著者として１０編以上の論文を公表している。

上述のように一連の斜入射分光器の考案・改良により軟X線から真空紫外域の分光研究分野に大きく貢献したと言え、また論文の記述も十分な情報が良く整理されており優秀である。

よって、本審査委員会は、その独創性と当該分野への貢献の程度から判断して、本論文が博士学位論文として十分の資格があると認めた。

論文審査委員全員の前で出願者に口頭試問を実施し、論文内容に関する質疑及び関連する光学や物性物理などの基礎知識についての試験を行った。その結果、質疑への対応は的確であり、且つ、十分に研究内容を理解していることが示された。基本的事項についても、関連している物理について十分に理解していると考えられる。

以上により、博士論文を合格とした。