Diffraction Gratings

The Crucial Dispersive Component

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Several times in the short life of this column, I have urged readers to contact me with their comments and suggestions for future topics. Implicit in that request was the potential for my asking you to actually write the article (after all, that's the price one pays for having initiative; see where it got me?). Chris Palmer of the Milton Roy Company is my first victim. I hope the readers agree that he carries the column's torch very well. I should add that he almost got out of it by telling me that his wife was, in his words, "8.95 months pregnant." Fortunately, he came through — with the article, that is. (P.S. to Chris and wife: congratulations and best wishes.)

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Contributing editor

In previous installments, the nature of light (1) and its interaction with matter (2) — the fundamental physical process in spectroscopy — were discussed. The spectrometer, the apparatus for studying this interaction, was also addressed (3). In this installment, we discuss the dispersive optical element fundamental to most spectrometers; the diffraction grating. Gratings provide the wavelength selection in spectrometers, an essential part of reducing the amount of experimental data in emission and absorption spectroscopy to manageable levels that allow interpretation.

WHAT IS A GRATING?

A diffraction grating is an optical element similar to a lens or a mirror superimposed with a precise pattern of microscopic periodic structures. Usually this pattern is a corrugated surface of grooves (a surface-relief grating), though some gratings are formed by the periodic variation of the refractive index inside the grating itself (a volume grating). Gratings used to disperse ultraviolet (UV) and visible light usually contain between 300 and 3000 grooves/mm, thus the distance between adjacent grooves is ~1μm.

A reflection grating's corrugated surface is coated with a metal to enhance reflectivity. Transmission gratings do not have a metal coating; the incident light is diffracted upon transmission through the grating. Most commercial spectrometers use reflection gratings because the optical system folds upon itself and the optical characteristics of reflection gratings are often more suitable for the particular application than those of transmission gratings.

WHAT DOES A GRATING DO?

Light incident on a grating is dispersed. Dispersion is the phenomenon by which a spectrum of light is separated in space by wavelength (Figure 1). Prisms also disperse light by wavelength and can be used in spectrometers, although grating-based dispersing instruments offer a number of advantages, so few commercially available instruments use prisms. Although prisms disperse light through refraction, gratings do so by diffraction.

Interaction of radiation with matter possessing a regular periodic structure at or near the same size as the wavelength of the radiation exhibits diffraction. For example, diffraction is well-known in x-ray crystallography, in which a beam of x-rays incident on a crystalline sample diffracts due to the regular placement of molecules in the crystal. A more common example of diffraction is the variety of colors seen from the surface of a compact disc.

HOW DOES A GRATING WORK?

A diffraction grating can be thought of as a collection of narrow slits. Multiple-slit interference can then be used to model the effects of a grating on incident light. Light of a single wavelength passing through the grating (or reflected from the grating) is diffracted by the grooves; in most directions the light diffracted from one groove cancels that diffracted from other grooves through destructive interference. In a certain finite number of directions, though, all of the rays from the grooves interfere constructively. Such directions correspond to different diffraction orders. Many orders exist when the wavelength of the light diffracted is much smaller than the distance between adjacent grooves; few orders exist when this wavelength is comparable to the groove spacing, and no orders exist except the reflected ray when the wavelength exceeds 2× the groove spacing (in the last case the grating behaves as a mirror).

WHERE ARE GRATINGS FOUND?

Gratings are found in most optical spectrometers, covering UV, visible, and IR

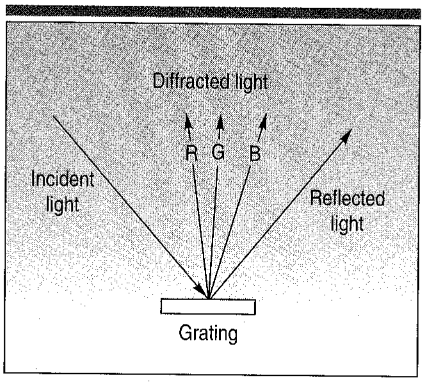

Figure 1. White light incident on a reflection grating is diffracted; its component wavelengths emanate in different directions. Note that there is also a white reflected beam; the grating also acts as a mirror. The figure for a transmission grating would show the reflected and diffracted light below the grating. R = red light, G = green light, B = blue light.

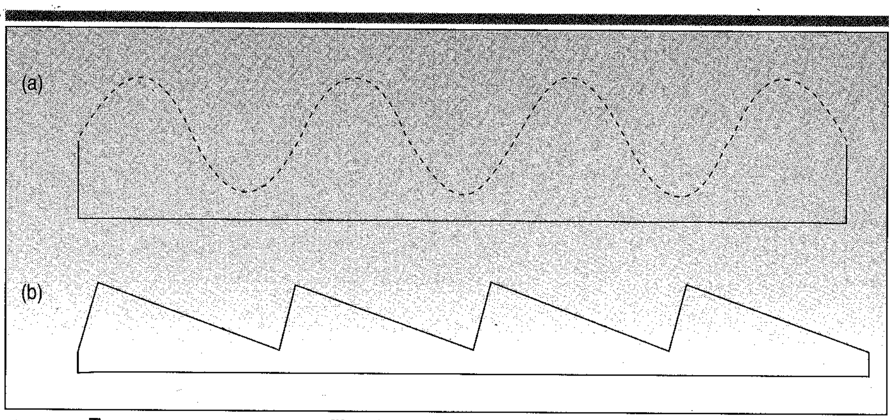

Figure 2. Two common groove profiles (the grating is shown in cross section). **(a)** A sinusoidal profile; **(b)** a triangular (blazed) profile.

spectra. Absorption and emission spectrometers, fluorometers, inductively coupled plasma (ICP) instruments, and high-performance liquid chromatography (HPLC) equipment all use grating spectrometers. Large research spectrometers, such as those that analyze very short wavelength light (for example, extreme UV and x-ray light) from synchrotron radiation beamlines, also use gratings. Large gratings are used in astronomical telescopes allowing light from objects in space to be analyzed spectroscopically. Gratings are also used for tuning lasers and compressing and stretching laser pulses.

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Not all spectrometers use gratings; mass spectrometry, for example, disperses matter by velocity rather than radiation by wavelength, and Fourier transform infrared (FT-IR) spectrometers accomplish wavelength differentiation using an interferometer rather than a monochromator.

HOW ARE GRATINGS MADE?

Commercial surface-relief gratings are produced using an epoxy casting process called *replication.* This process involves pouring a liquid into a mold, allowing the liquid to harden, and then removing the hardened material from the mold without damaging either. The replication process yields optically identical copies of the original grating, called the *master grating.*

The vast majority of master gratings are formed in one of two ways: by mechanical ruling, in which a diamond is dragged across a metallized substrate to produce a series of parallel grooves, or by interference methods, in which the fringe pattern formed by two coincident laser beams exposes a photosensitive blank, creating all grooves at once. The latter method produces gratings commonly termed *holographic.* Because making one high-quality master grating can take weeks, without a replication process grating-based spectrometers would not be commercially available.

The surface corrugation of a grating is usually one of two types. A sinusoidal profile (Figure 2a) is characteristic of many holographic gratings. A triangular "staircase" profile (Figure 2b) is commonly created by mechanical ruling. The triangular profile can generally be designed to diffract more light into a particular order (for a given range of wavelengths) than a sinusoidal profile can. As a result, gratings with triangular groove profiles are universally called *blazed* gratings (because of the brightness of their spectra). Replication preserves the profile of the master grating faithfully throughout the family of replicas made from it, thus their optical performance matches that of the master.

Since the development of replication techniques in the 1950s, the diffraction grating has supplanted the prism in commercial spectrometers. This is fortunate because gratings provide a number of advantages over prisms. Prisms that transmit visible light absorb most UV and IR wavelengths, whereas reflection gratings can be suitably coated for high reflectivity in wide spectral regions. Grating instruments can also be designed with constant slits; prism instruments usually require wider slits for shorter wavelengths. Grating instruments are generally smaller than prism instruments of similar specification, a timely advantage as instrumentation moves toward portability. With the advent of low-cost, high-fidelity replication technology, gratings have become the dispersing element of choice in most modern dispersive optical systems.

REFERENCES

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Further reading: M.C. Hutley, Diffraction Gratings (Academic Press, London, 1982).

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