10.3.2.1.3 Optical components of dispersive spectral instruments

An *entrance collimator* (see Fig. 10.5) is an optical arrangement for the production of a quasi-parallel beam of radiation of a required cross section. It consists of an objective lens or mirror, the cross section of which constitutes the *entrance aperture stop* and an *entrance field stop* at the front focal plane of the collimator. The entrance aperture stop may also form the limiting aperture stop, the *entrance pupil* of the whole apparatus.

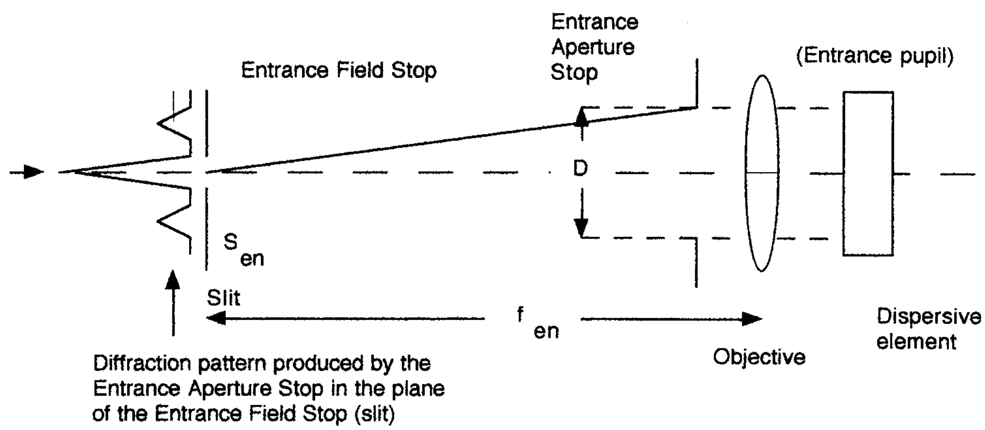

Fig. 10.5 Defining the optimal slit width in units of the virtual diffraction pattern produced by the entrance aperture stop in the plane of the entrance field stop

The entrance field stop in most dispersive instruments is a *slit*, the *entrance slit*. Both *curved slits* and *straight slits* are used. Distinguishing features are the *slit length* (see Note 1) and the *slit width*. Slits are either fixed or adjustable. They can be straight or curved depending on the optical design. An optical instrument may contain several real or virtual aperture and field stops. Those which determine the maximum throughput of radiant power are called the *limiting stops*.

Distinguishing features of the lenses or mirrors in the collimator systems are the *collimator focal length*, f_{en}, (see Note 2) and the *relative aperture*. The relative aperture is defined in terms of the diameter D for circular entrance aperture stops and in terms of the effective diameter D_{eff}, where

$$D_{eff} = \left(\frac{4 B_{en} H_{en}}{\pi} \right)^{1/2}$$

for rectangular entrance aperture stops of width B_{en} and length H_{en}. The relative aperture k_{en} (see Note 3) is then defined by the expression

$$k_{en} = \frac{f_{en}}{D} \text{ for circular apertures}$$

$$k_{en} = \frac{f_{en}}{D_{eff}} \text{ for rectangular apertures}$$

The expressions

Note 1 The term *slit height* may be used when the slit is positioned vertically.

Note 2 In this section the subscripts 'en' for entrance and 'ex' for exit are used.

Note 3 The words f-number and optical speed are discouraged.

$$k_{B,\text{en}} = \frac{f_{\text{en}}}{B_{\text{en}}} \quad \text{and} \quad k_{H,\text{en}} = \frac{f_{\text{en}}}{H_{\text{en}}}$$

are also useful.

Distinctive characteristics of the dispersive element components are:

- the *total angle of deviation* θ;
- the *angular dispersion* $d\theta/d\lambda$ with respect to the wavelength λ;
- the theoretical resolving power

$$R_0 = \frac{\lambda}{d_0\lambda}$$

- the *upper* and *lower wavelength limits*, λ_u and λ_l between which the *transmission (or reflection) factor* exceeds a specified fraction of its maximum.

The characteristic quantities of prisms are:

- shape and type of the prism;
- the material from which it is made and its *refractive index n* which is a function of the wavelength λ;
- the *material dispersion* $dn/d\lambda$, which also changes with the wavelength;
- the *linear absorption coefficient* of the material;
- the *effective base length* b_{eff}, which is the path difference between the longest and the shortest possible parallel rays closest and farthest from the base, respectively;
- the *prism angle* α;
- the *prism height* parallel to the *refractive edge*

The following terms are derived from these quantities:

- *the theoretical resolving power*

$$R_0 = b_{\text{eff}} \frac{dn}{d\lambda}$$

- The *angular dispersion* (in radians per wavelength)

$$\frac{d\Theta}{d\lambda} = \frac{b_{eff}}{B_W}\frac{dn}{d\lambda}$$

where B_W is the width of the refracted *optical beam* in the plane of refraction.

Diffraction gratings may be transmission or reflection types. They are *dispersive* optical components with *grooves* (see Note 4) or *lines* parallel to each other. *Ruled gratings* are mechanically produced by a *ruling engine* whereas diffraction gratings (see Note 5) are made by interaction of an interference pattern with a photosensitive layer, e.g., a photographic emulsion. The grooves have a periodic structure in the direction of dispersion.

Replica gratings are duplications of the *master grating* (original grating). It is possible to repeat the process of replication for several generations.

Characteristic quantities of gratings include:

- the *grating width* W of the grooved area (measured in a direction at right angles to the grooves, in the plane of the grating);
- the length of the grooved area (measured parallel to the grooves);
- the total *number of grooves* N_r. We have:

  $N_r = n_r W$,

  when n_r is the number of grooves per unit of length across W;
- the *grating constant* d which is the reciprocal of n_r;
- the *grating function* (formula) is the function relating the *angle of incidence* ϕ_1 to the *angle of diffraction* ϕ_2; i.e.:

$$\sin\phi_1 + \sin\phi_2 = m\frac{\lambda}{d}$$

  where m is the *order of diffraction*

- the *efficiency of the grating* $\eta(\lambda)$ is the ratio of the *diffracted* to the *incident spectral radiant power*.

Note 4 The word '*rulings*' is generally used when mechanically ruled gratings are described. With interferometric gratings, the recommended term is 'lines'.

Note 5 The term 'holographic' grating is incorrect and should not be used.

$$\eta(\lambda) = \frac{\Phi_\lambda(out)}{\Phi_\lambda()}$$

- the *usable free spectral range*, (without *order overlap*):

$$\Delta\lambda = \frac{\lambda}{m}$$

- the *blaze* is the direction of optimum efficiency $\eta(\lambda)$ of the grating;
- the *blaze angle* γ_B. With *saw-tooth shaped grooves*, γ_B represents the angle between the *grating normal* and the normal of the groove surface.
- the *blaze wavelength* λ_B is that wavelength or wavelength range at which blaze occurs. With plane gratings the blaze wavelengths are given for autocollimation;

From these quantities the following can be calculated:

- the *theoretical resolving power*:
  $R_o = m\ N_r$
- the *angular dispersion* (in radians per wavelength):

$$\frac{d\phi_2}{d\lambda} = \frac{R_0}{B_W};$$

Plane gratings have lines on a flat surface. They consequently have no optical imaging properties.

Echelle gratings have lines on a concave surface. The surface may be spherical, toroidal or elliptical. Concave gratings are generally used as objective components forming part of or acting fully as the collimator and/or camera of the instrument.

The *Fabry-Perot interferometer* is an example of a multiple-beam interferometer which enables high resolution measurements to be made by using the interference of multiple beams of monochromatic radiation at very high orders, after reflection between two surfaces. A special case of such an interferometer is the *Fabry-Perot etalon interferometer* in which the thickness of a plane parallel plate of air or of another gas between the two surfaces remains unaltered. Another special case is the *etalon plate interferometer* basically consisting of a transparent solid plate with the reflective coating applied to the two surfaces.

Characteristic quantities are:

- the separation, *a*, between the (plane or concave) reflecting surfaces:
- the radius of curvature (with concave mirrors);
- the *reflection factor*, ρ, of the mirrors;
- the *refractive index*, *n*, of the medium between the reflecting surfaces which relates the wavelength, λ, in the medium to that in vacuum by

$$\lambda = \frac{\lambda_{\text{vac}}}{n};$$

The following properties can be expressed in these quantities:

- the *order of interference*:

$$m = \frac{2a}{\lambda} = \frac{2an}{\lambda_{\text{vac}}};$$

- the *free spectral range*:

$$\Delta\lambda = \frac{\lambda}{m};$$

- the *finesse*:

$$F = \frac{\Delta\lambda}{\delta_{\text{o}}\lambda}$$

where $\delta_{\text{o}}\lambda$ is the resolved wavelength distance.

The following distinctions can be made:

- *theoretical finesse* (or *reflectivity finesse*)

$$F_0 = \frac{\Delta\lambda}{\delta_o\lambda} = \frac{\pi\rho^{1/2}}{1-\rho};$$

where $\delta_o\lambda$ is the theoretical resolution;

- *surface defects finesse*:

$$F_1 = \frac{\Delta\lambda}{\delta_{\mathrm{d}}\lambda} = \frac{\rho}{2},$$

where λ/ρ denotes the maximum deviation of the plate surface from the ideal one, usually measured at $\lambda = 546.1$ nm;

- *scanning finesse*:

$$F_{\mathrm{s}} = \frac{\Delta\lambda}{\delta_{\mathrm{s}}\lambda} = \frac{2\pi\Delta\lambda}{\Omega\lambda};$$

where Ω is the solid angle subtended by a scanning aperture:

- *effective instrumental finesse* F_ρ is the result of a convolution of the previous forms of finesse.

- the *theoretical resolving power*

$$R_0 = mF_0 = \frac{2a}{\lambda}F_0 = \frac{2an}{\lambda_{\mathrm{vac}}}F_0;$$

- the angular dispersion $\mathrm{d}\rho/\mathrm{d}\lambda$, where ρ is the angle of diffraction

The *exit collimator* is an optical arrangement for the production of spectra as uniform adjacent images of the entrance slit. If the imaging optical system is supplemented by a two-dimensional radiation detector in the focal plane, the whole system is then called a *camera*. Alternatively, the exit collimator may contain one or more exit slits. The objective optical system may consist of one or more lenses and mirrors. Quantities of importance are:

- the *focal length* f_{ex};
- the relative aperture k_{ex};
- the usable length of the focal plane;
- the *inclination angle* Θ_{ex} between the normal to the focal plane and the optical axis;
- the *linear dispersion* dx/dλ in which x is the spatial coordinate in the direction of dispersion in the focal plane;
- *reciprocal linear dispersion* is the inverse of the linear dispersion.