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Understanding and selecting diffraction gratings

Diffraction gratings are used in a variety of applications where light needs to be spectrally split, including engineering, communications, chemistry, physics and life sciences research. Understanding the varying types of grating will allow you to select the best option for your needs.

An introduction to diffraction gratings

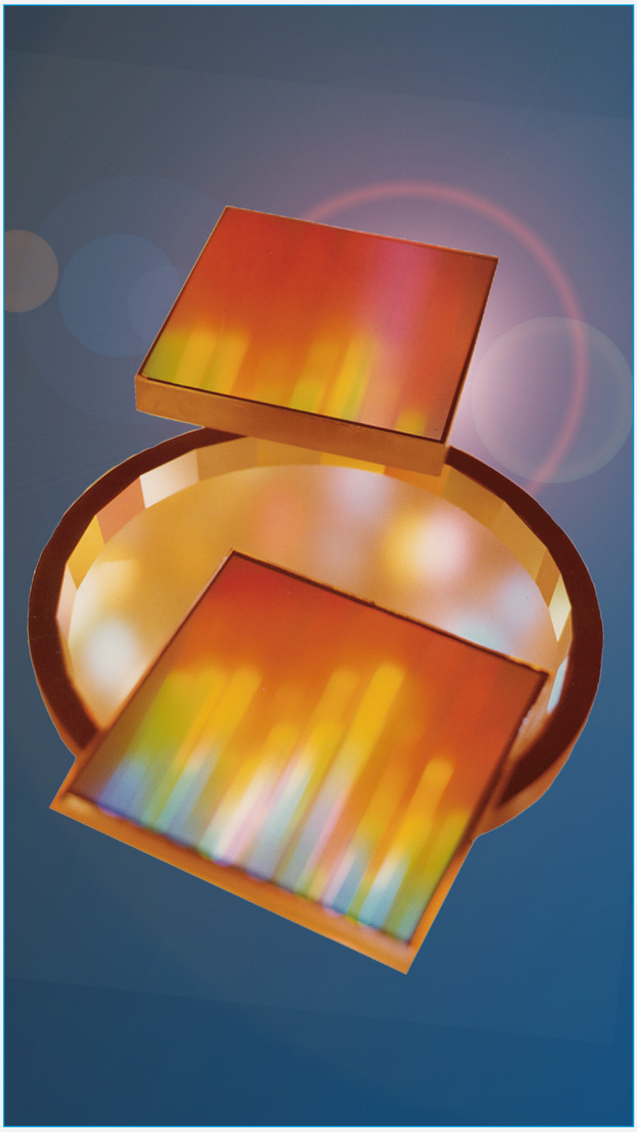
Diffraction gratings are passive optical components that produce an angular split of an incident light source as a function of wavelength. Each wavelength exits the device at a different angle, allowing spectral selection for a wide range of applications.

Typically, a grating consists of a series of parallel grooves, equally spaced and formed in a reflective coating deposited onto a suitable substrate. The distance between each groove and the angles the grooves form in respect to the substrate influences both the dispersion and efficiency of a grating. If the wavelength of the incident radiation is much larger than the groove spacing, diffraction will not occur. If the wavelength is much smaller than the groove spacing, the facets of the groove will act as mirrors and, again, no diffraction will take place.

There are two main classes of grating, based on the way the grating is formed:

Ruled gratings – a diamond, mounted on a ruling engine physically forms grooves into the reflective surface.

Holographic gratings – groves are formed by laser-constructed interference patterns and a photolithographic process.



Each of these types of grating has different optical characteristics. It is therefore important to choose the best type of grating for your application.

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Ruled gratings

Precision and preparation are the keys to producing ruled gratings successfully. The substrate used is often glass or copper, and is highly polished to produce a flat, smooth surface. This surface is then coated with a thin layer of aluminium, which is reflective. The ruling engine needs to be precisely set up to form exact lines with accurate spacing between them. The set-up and test of the machine can take several days and test rulings are made to ensure absolute precision as mistakes when ruling onto the substrate can be expensive. Only when the ruling engine is completely ready will the grating be ruled.

This process can occasionally form "ghost" rulings and stray light, but also produces high-efficiency gratings that are particularly useful for radiation-induced reactions and applications.

Holographic gratings

Initial preparation for holographic grating production is similar to that for ruled gratings, but the coating used for a holographic grating is a photosensitive material rather than a reflective one. Once coated, the substrate is then positioned between intersecting laser beams –producing monochromatic and coherent light – producing interference fringes. These intersecting beams generate grooves with complete precision, producing consistent gratings with none of the errors seen with ruled gratings. This means that holographic gratings generate much less stray light. Once the grooves have been generated, the substrate is coated with a reflective material.

Replicating diffraction gratings

Although it may take time to produce an initial precise ruled or holographic grating, a replication process exists, allowing copies to be made from a master grating. These replicas can be made very accurate and repeatable, one of the reasons that exact gratings are available on a commercial basis.

Which diffraction grating is best for your application?

It is important to take the time to select the right diffraction grating for your requirements. This means assessing what you need the grating to achieve, the environment you will be working in and the equipment you will be using. There are three main grating characteristics that you will need to consider before making your selection:

Efficiency
There are several factors that affect the efficiency of a diffraction grating. These include the shape of the grooves, the reflectance of the coating and the angle of groove incidence. You will need to consider the absolute efficiency – the percentage of incident monochromatic radiation that is diffracted – and the relative efficiency, which is a comparison of the energy diffracted into the desired order with the energy diffracted by a plane mirror that has been treated with the same coating as the grating. Using these factors to define efficiency, ruled gratings are usually more efficient than holographic ratings.

Blaze wavelength
The term "blaze angle" is used to describe the angle on a ruled grating that is created by the longer side of the groove and the plane of the grating. The blaze angle occurs on ruled gratings because the diamond-cutting process produces a sawtooth profile with one side longer than the other. Changing this blaze angle to concentrate diffracted radiation to a specific region of the spectrum increases the efficiency of the grating. Where the maximum efficiency occurs, this is known as the "blaze wavelength." This is usually a characteristic of ruled gratings because holographic gratings have grooves with equal sides, however, this can be altered in some cases and, where the spacing-to-wavelength ratio is near 1, a holographic grating and a ruled grating are virtually equally efficient.

Wavelength range
The distance between each groove on both ruled and holographic gratings determines their spectral range. Therefore, the wavelength range required by your application will determine the desired groove spacing on whichever type of grating is best for your needs.

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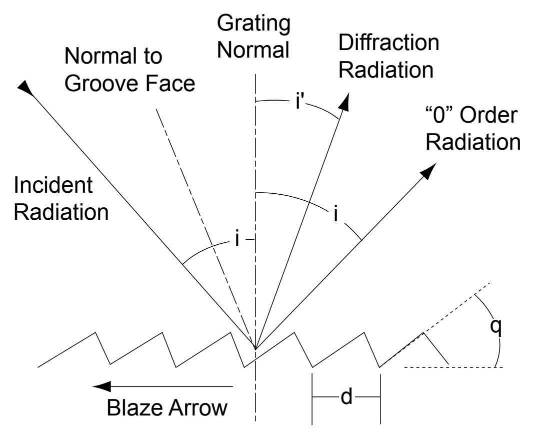
Additional factors to consider

Depending on the application, there may be other factors to consider when selecting a diffraction grating. These include Echelle gratings, where groove density and shape are optimized for use at high diffraction orders and with high damage thresholds. You may also choose to vary the size and shape of your grating. Typically, gratings are square and rectangular, with sizes not exceeding 50mm square. However, you may request non-standard sizes, and that the grooves be cut parallel to the long dimension rather than the short dimension, which is usual.

The grating equation

Usually written as: **$n\lambda = d(\sin i + \sin i')$** where n is the order of diffraction, λ is the diffracted wavelength, d is the grating constant (the distance between successive grooves), i is the angle of incidence measured from the normal and i' is the angle of diffraction measured from the normal. For a specific diffracted order (n) and angle of incidence (i), different wavelengths (λ) will have different diffraction angles (i'), separating polychromatic radiation incident on the grating into its constituent wavelengths.



Grating angles and terms.

Resolving power :

The resolving power of a grating is the product of the diffracted order in which it is used and the number of grooves intercepted by the incident radiation. It can also be expressed in terms of grating width, groove spacing and diffracted angles. The "theoretical resolving power" of a diffraction grating with N grooves is: $\lambda/\Delta\lambda = Nn$.

The actual resolving power of a grating depends on the accuracy of the ruling, with 80-90% of theoretical being typical of a high quality ruling. Resolving power is a property of the grating and is not, like resolution, dependent on the optical and mechanical characteristics of the system in which it is used.

System resolution :

The resolution of an optical system, usually determined by examination of closely spaced absorption or emission lines for adherence to the Raleigh criteria ($R = \lambda/\Delta\lambda$), depends not only on the grating resolving power but on focal length, slit size, f number, the optical quality of all components and system alignment. The resolution of an optical system is usually much less than the resolving power of the grating.

Dispersion :

Angular dispersion of a grating is a product of the angle of incidence and groove spacing. Angular dispersion can be increased by increasing the angle of incidence or by decreasing the distance between successive grooves. A grating with a large angular dispersion can produce good resolution in a compact optical system.

Angular dispersion is the slope of the curve given by $\lambda = f(i)$. In autocollimation, the equation for dis¬persion is given by: $d\lambda/di = \lambda / 2 \tan i$

This formula may be used to determine the angular separation of two spectral lines or the bandwidth that will be passed by a slit subtending a given angle at the grating.

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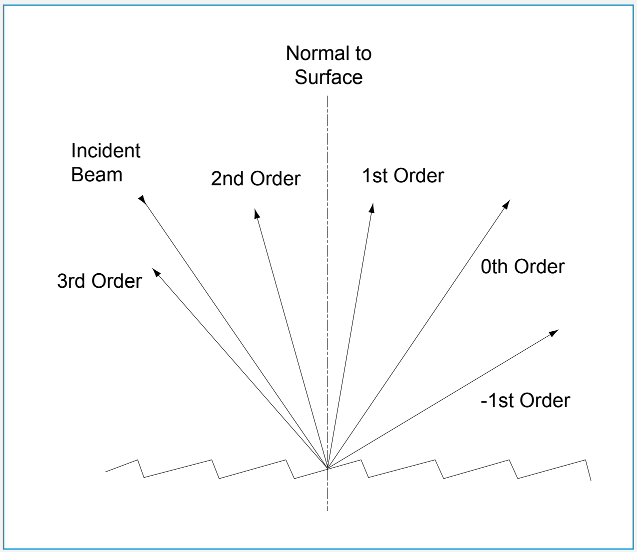
Diffracted orders :

For a given set of angles (i,i´) and groove spacing, the grating equation is valid at more than one wavelength, giving rise to several "orders" of diffracted radiation. The reinforcement (constructive interference) of diffracted radiation from adjacent grooves occurs when a ray is in phase but retarded by a whole integer. The number of orders produced is limited by the groove spacing and the angle of incidence, which obviously cannot exceed 90 degrees. At higher orders, efficiency and free spectral range decrease while angular dispersion increases. Order overlap can be compensated for by the judicious use of sources, detectors and filters and is not a major problem in gratings used in low orders.



Diffracted orders.

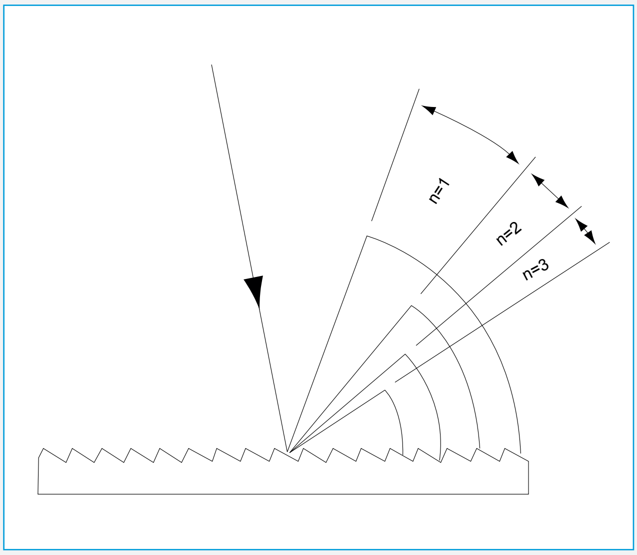
Polarisation:

Typical efficiency curves illustrate that, in all cases, orienting the polarisation of the E vector (P-Plane) perpendicular to the grooves (E) increases the efficiency over a specific wavelength region. This should be considered when optimizing the figure of merit (Q) of a cavity, particularly when it is polarized by auxiliary components such as Brewster angle windows.

Free spectral range :

Free spectral range is the maximum spectral bandwidth that can be obtained in a specified order without spectral interference (overlap) from adjacent orders. As grating spacing decreases, the free spectral range increases. It decreases with higher orders. If λ1, λ2 are lower and upper limits, respectively, of the band of interest, then:

Free spectral range = $\lambda 2 - \lambda 1 = \lambda 1/n$



Higher orders and free spectral range

Ghosts and stray light :

Ghosts are defined as spurious spectral lines arising from periodic errors in groove spacing. Interferometrically controlled ruling engines minimize ghosts, while the holographic process eliminates them.

On ruled gratings, stray light originates from random errors and irregularities of the reflecting surfaces. Holographic gratings generate less stray light because the optical process which transfers the interference pattern to the photoresist is not subject to mechanical irregularities or inconsistencies.

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Echelle gratings :

Echelle Gratings are optimized (groove density and shape) for use at high diffraction orders (and high incidence angle). Damage thresholds as high as 250 watts/cm2 for CW sources are available for use of those gratings into dye or tunable lasers.

Transmission gratings:

Blazed transmission gratings are designed for optimum performance in the visible and NIR spectrum, offering different levels of dispersion. In most cases, the efficiency is comparable to that of reflection gratings typically used in the same region of the spectrum. Transmission gratings offer a basic simplicity for optical designs that can be beneficial in fixed grating applications such as spectrographs. The incident light is dispersed on the opposite side of the grating at a fixed angle.

Transmission gratings are very forgiving for some types of grating alignment errors. By necessity, transmission gratings require relatively coarse groove spacing to maintain high efficiency. As the diffraction angles increase with the finer spacing, the refractive properties of the materials used limit the transmission at the higher wavelengths and performance drops off. The grating dispersion characteristics, however, lend themselves to compact systems utilizing small detector arrays. The gratings are also relatively polarization insensitive. Transmission gratings can be made with AR coatings. In addition to increasing the throughput of the grating, an AR coating eliminates any secondary spectra concerns caused by the back surface reflection. Please note, however, that AR coatings are designed for peak performance at a specific wavelength and may detract from grating efficiency outside the design wavelength range.

UV Transmission Gratings are also available in standard sizes. They are manufactured with carefully selected UV materials allowing for optimal performance down to 235 nm. Zero order data is included in all performance curves for those interested in beam splitting applications.

Transmission grating beamsplitters:

Transmission grating beamsplitters are commonly used for laser beam division and multiple laser line separation in visible wavelengths. The transmitted beam is diffracted into multiple orders. Transmission grating beamsplitters consist of an index matched epoxy replica on a polished glass substrate for a high total efficiency. These beamsplitters are usually designed specifically for useful division of He-Ne lasers.

Several gratings are available offering different dispersion and power distributions. The diffraction angle for any wavelength may be calculated using the grating equation for normal incident light :
$\theta n = \sin-1\ (n\lambda / d)$ where:

θn = diffraction angle for the nth order
n = diffracted order
λ = wavelength of light
d = grating period

Coatings :

Gratings used in the ultraviolet, visible and infrared are normally replicated with an aluminum coating. Aluminum is used rather than silver because it is more resistant to oxidation and has superior reflectance in the ultraviolet. Aluminum averages over 90% reflectance from 200 nm to the far infrared, except in the 750 to 900 nm region where it drops to approximately 85%. When maximum reflectance is required in the near infrared, as is the case with some fiber optic applications, the aluminum coating may be overcoated with gold. Though gold is soft, it is resistant to oxidation and has a reflectance of over 96% in the near infrared and over 98% above 2.0 µm. The reflectance of gold drops substantially below 600 nm and is not recommended for use in the visible or ultraviolet regions.

Dielectric overcoatings such as aluminum magnesium fluoride (AlMgF2) protect aluminum from oxidation, maintaining the original high reflectance of aluminum in the visible and ultraviolet. While gold overcoating can increase reflectivity, any overcoating may reduce the damage threshold by a factor of two or more.

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Molecular lasers gratings :

Molecular Lasers gratings are original rulings or replicas that are normally used as end reflectors for tuning molecular lasers. The output wavelength of a molecular or dye laser can be tuned by rotating a Littrow mounted grating around an axis parallel to the grooves. The grating equation:

$n\lambda = d(\sin i + \sin i')$

where n is the order of diffraction, λ is the diffracted wavelength, d is the grating constant (the distance between successive grooves), i is the angle of incidence measured from the normal and i' is the angle of diffraction measured from the normal, reduces to $n\lambda = 2d \sin i$ for the Littrow configuration.

The angle of incidence (i) is adjusted to select the output wavelength while creating a narrow gain profile.

Grazing incidence gratings:

Holographic gratings (0.5" x 2") with a typical efficiency of 24%, single pass, and a similarly sized mirror, are suitable for use in the grazing incidence configuration.

Grazing incidence is a simple and inexpensive optical configuration, as described in Applied Optics, July 1978, p. 2224, that can tune and increase the resolution of a dye laser. A holographic grating, functioning as an end reflector in a dye laser cavity, is positioned so that laser radiation strikes the grating almost perpendicular to the grating normal. As the angle of incidence approaches 89 degrees, a relatively large area of the grating is illuminated by the laser beam, increasing angular dispersion and resolving power significantly. The sizes of the grating and mirror (12.7 mm x 50.8 mm usually) are optimized for grazing incidence and minimize the cost of the components. The grating is fixed and tuning is achieved by rotation of the mirror. The laser beam is diffracted twice in grazing incidence, resulting in a twofold increase in resolution. Low grating efficiency is characteristic of the grazing incidence configuration but is compensated for by the high gain of the dyes used. Grazing incidence grating are available with a P-type or CW-type replication coating for higher damage threshold performance.

Damage thresholds :

Most standard gratings are available with either P-type or CW-type replication coatings for higher damage threshold performance (contact us for more details).

Handling gratings :

The surface of standard gratings are coated with aluminum or gold and require extreme care when handling. Handling should be done by the edges only. These relatively soft coatings are vulnerable to fingerprints and numerous aerosols. Scratches or other cosmetic defects do not, unless extreme, usually affect optical performance. No attempt to clean a grating should be made without first consulting us.

How Acal BFi can help

We supply a range of diffraction gratings for a wide variety of research and commercial applications. Our team has the knowledge and expertise to advise you on the best type of diffraction grating for your needs and supply samples where needed. You can also come to us for help and advice once your grating is in use.

For more information or to talk to one of our dedicated team contact us today.

*Descriptions and diagrams courtesy of Optometrics Corporation.

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