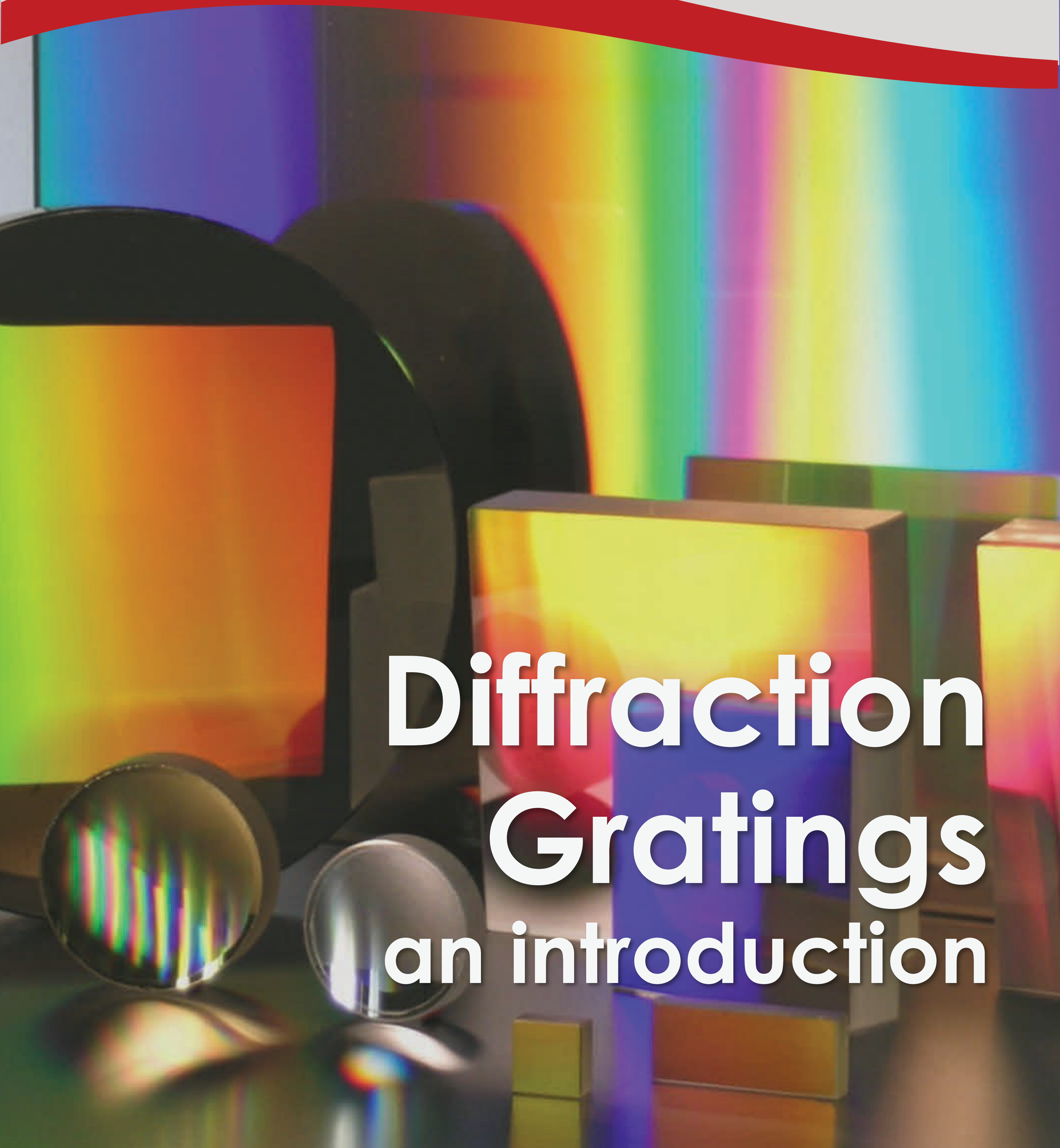
Spectrum Scientific, Inc.



Diffraction Gratings
an introduction

WHAT IS A DIFFRACTION GRATING?

A diffraction grating is an optical element that diffracts energy into its constituent wavelengths. The major difference between a diffraction grating and a prism is that the dispersion of a prism is non -linear while gratings offer linear dispersion. Gratings are also generally more efficient and do not suffer from absorption effects which limit the useful wavelength range of a prism.

The groove density, depth and profile of a grating dictates the spectral range, efficiency, resolution, and performance of the grating.

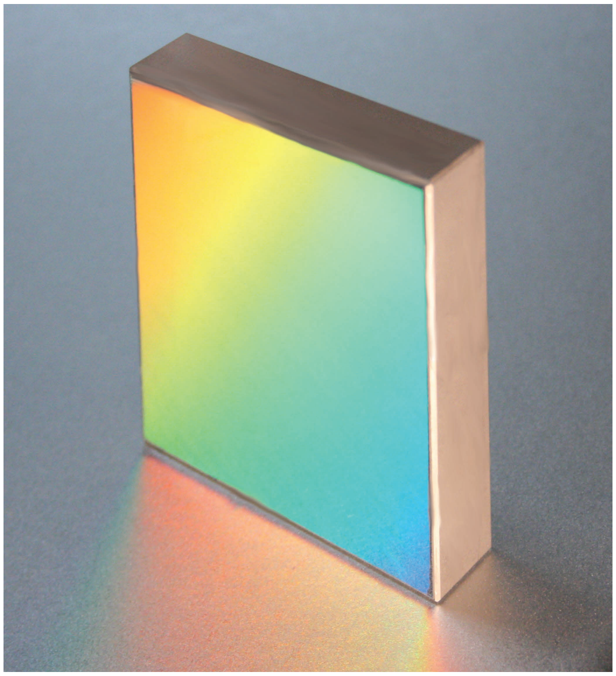
There are typically two different types of diffraction grating – the ruled grating and the holographic grating.

A ruled diffraction grating is produced by a ruling engine that cuts grooves into the coating on the grating substrate (typically glass coated with a thin reflective layer) using a diamond tipped tool. A holographic diffraction grating is produced using a photolithographic technique.

A diffraction grating can be a reflection grating or a transmission grating, however, this guide will primarily focus on reflection gratings.

The most common type of reflective diffraction gratings are plane and concave gratings although they can also be other profiles such as convex or toroidal depending on the application.

A diffraction grating usually consists of three layers – the substrate (usually glass), an epoxy or metallic layer in which the grooves are created and a reflective coating. Gratings can have a sinusoidal or blazed profile.A sinusoidal grating generally offers lower efficiency than a blazed grating, but often gives a broader spectral



coverage. A blazed grating has a 'saw tooth' profile and normally offers higher efficiency over a defined spectral range.

Reflection gratings are normally coated with a reflective coating, usually aluminum with a protective overcoat for UV-VIS-NIR use or gold for IR use. Transmission gratings are usually supplied with an antireflection coating.

A commercial diffraction grating is generally a replica grating produced from a sub-master, which may be several generations down from the master diffraction grating.

Typically, the cost of producing a master diffraction grating is expensive and by supplying replica gratings (which offer almost indistinguishable performance), one master may produce thousands of replicas, lowering the unit cost of the diffraction grating.

GRATING EQUATION

The general grating equation for reflective gratings is written:

$$n\lambda = \mathrm{d}(\sin\theta_i + \sin\theta)$$

where

n = Order of Diffraction
λ = Diffracted Wavelength
d = Grating Constant (distance between grooves)
θ_i = Angle of Incidence (measured from the normal)
θ = Angle of Diffraction (measured from the normal)

This equation allows you to very precisely predict the direction of light for any given wavelength.

GRATING DISPERSION

Diffraction gratings are used to split light into separate wavelengths, or to disperse the light.

Angular dispersion is a correlation between a change in the diffraction angle and a small change in wavelength. Angular dispersion is:

$$\frac{k * n}{Cos(b)}$$

where

b = Diffracted Angle
k = Diffracted Order
n = Groove Density

Linear dispersion will vary with the distance from the grating to the detector. Linear dispersion is:

$$\frac{Cos(b)}{(k * n * L_B)}$$

where

b = Diffracted Angle
k = Diffracted Order
n = Groove Density
L_B = Distance from Grating to Detector

With these fundamental equations, one can design a spectral instrument with great accuracy. They are used to design spectral sensors used in laboratory spectrometers, hyperspectral imagers, telecommunication, pulsed laser and other devices found in modern optical systems.

GRATING EFFICIENCY

The efficiency of a grating is dependent upon several conditions:

- Wavelength
- Polarization
- Incident angle
- Diffracted order
- Groove shape
- Metallic overcoat (for reflection gratings)

The shape of the groove will greatly affect the diffracted energy of a reflective grating. The highest efficiencies for reflection gratings are achieved with blazed or sawtooth profile grooves (see figure 3). Therefore, it is common to request a blazed grating.

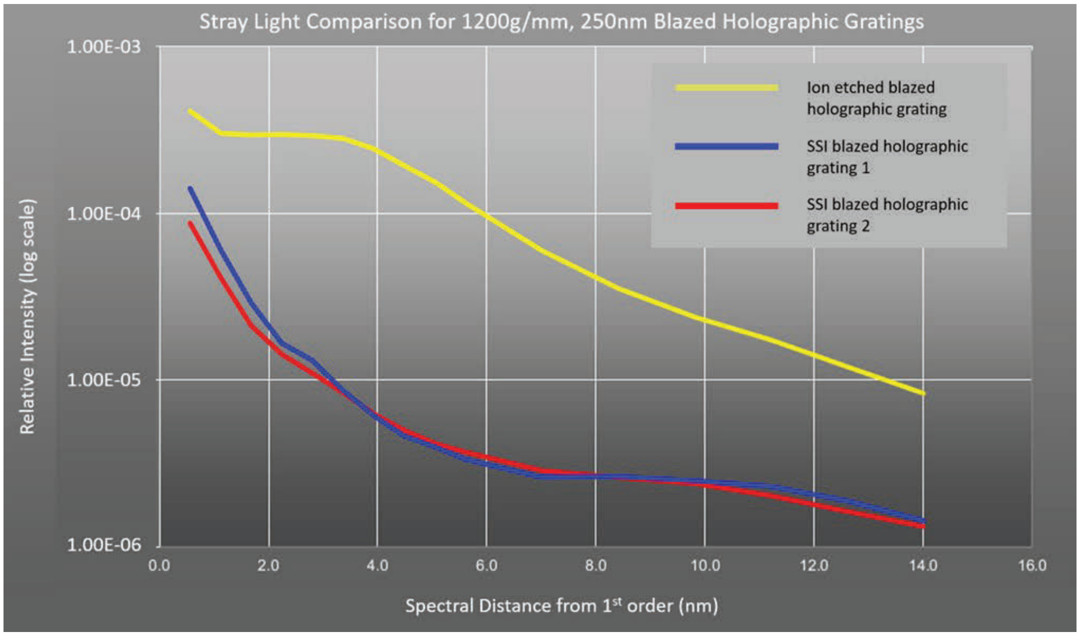
Several different methods can be used to blaze a grating. Spectrum Scientific uses a proprietary technique that can create UV blazed gratings which demonstrate higher efficiency compared to an ion etched blazed holographic grating.

STRAY LIGHT

Stray light is exhibited when wavelengths other than those selected appear at the measurement plane. It is generally caused by diffraction, light scattering from imperfections on the grating surface or ghost orders (eg periodic errors in the spacing of ruled gratings) that cause wavelengths to follow unintended paths within an optical system.

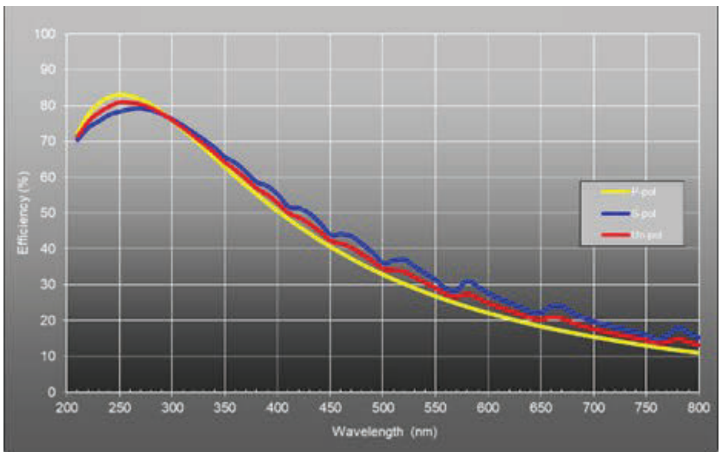
The effect of stray light is to give an apparent higher signal level at any given wavelength and negatively impact the signal to noise ratio (SNR).

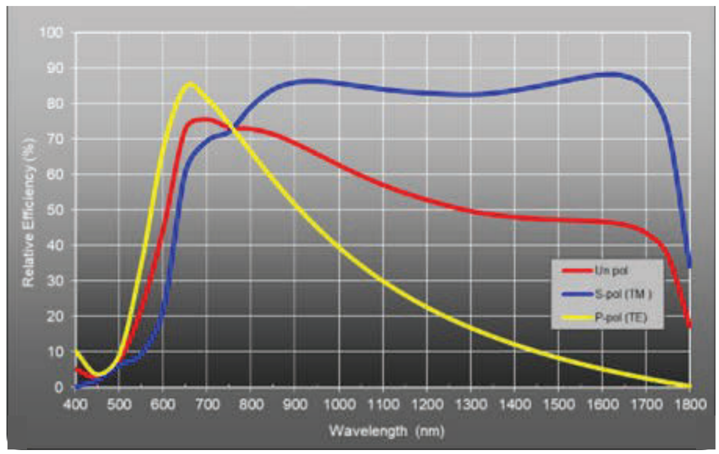
The proprietary blazing technique used by Spectrum Scientific significantly reduces stray light in blazed gratings, especially when compared to ion-etched holographic gratings.

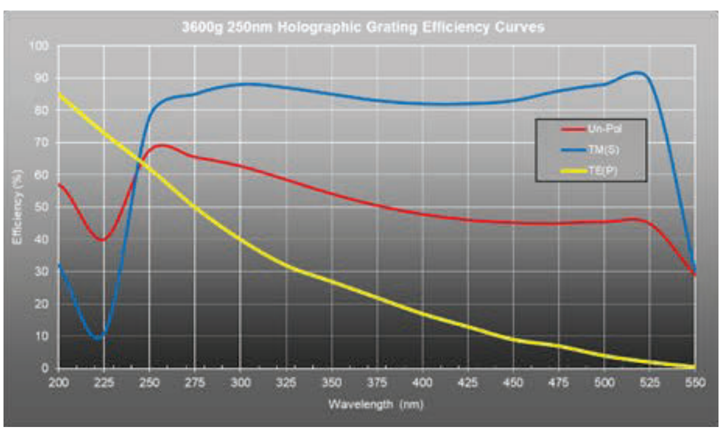


POLARIZATION

The polarization of the light source can greatly impact the efficiency of the grating. It is important to understand that the light energy diffracted from a grating often becomes polarized. Therefore, when illuminating the grating with unpolarized light, the resulting diffracted energy will be polarized as shown in the charts below. Higher groove frequencies increase the polarization separation.







Unless stated otherwise, most gratings are tuned for maximum efficiency for unpolarized light. However, some gratings will be marked with maximum efficiency for either P-polarization or S-polarization.

P-polarization, also known as TE polarization, is when the incident light is polarized parallel to the grating grooves. S-polarization, also known as TM polarization, is when the incident light is polarized perpendicular to the grating grooves.

It is interesting to note that the human eye can only see (or sense) the electric vector (E).

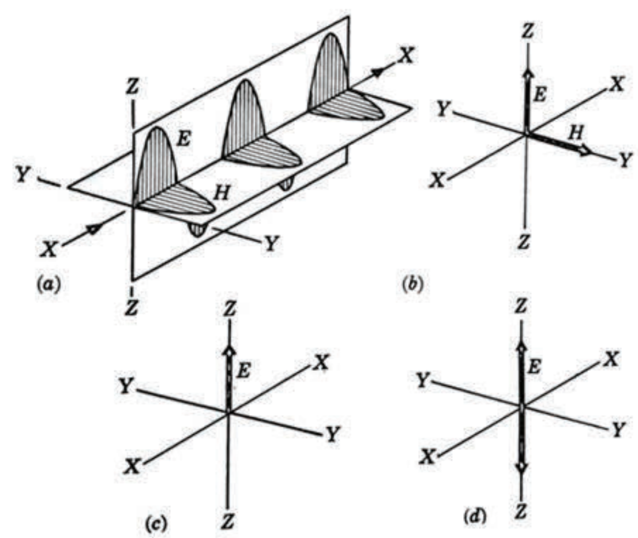


Figure 1. Light traveling in the X -direction is polarized in the YZ plane. "E" is the electric vector and in this diagram, it is parallel to the Z plane. "H" is the magnetic vector, and it is parallel to the Y plane.

RULED GRATING vs HOLOGRAPHIC GRATING

Due to the mechanical nature of the manufacturing process, ruled diffraction gratings cannot be produced without defects, which may include periodic errors, spacing errors and surface irregularities. All of these contribute to increased stray light and ghosting (false spectral lines caused by periodic errors).

Historically, ruled diffraction gratings offered higher efficiency than holographic diffraction gratings, but with the introduction of blazed holographic diffraction gratings this is no longer always the case.

The optical technique used to manufacture holographic diffraction gratings does not produce periodic errors, spacing errors or surface irregularities. This means that holographic gratings have significantly reduced stray light (typically 10x lower stray light compared to ruled gratings) and no ghosts.

In addition, concave gratings present specific problems for ruled gratings compared to holographic gratings. Ruled concave gratings cannot be utilized for flat field imaging applications as the projected groove pattern of the grating always results in straight, equidistant lines and therefore additional optics are required to correct for aberration. Holographic concave gratings, however, can be designed and produced with curved grooves that produce aberration corrected images. Holographic concave gratings can also be produced with lower f-numbers than ruled concave gratings.

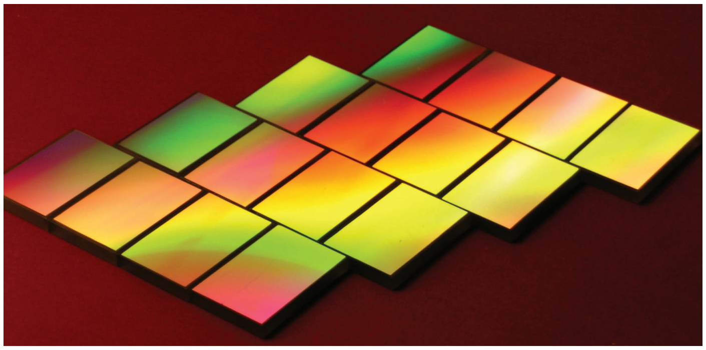
For nearly all applications a blazed holographic diffraction grating will offer significantly better overall performance when compared to a ruled diffraction grating. A ruled diffraction grating should only be used where groove density or spectral range requirements preclude the use of a blazed holographic diffraction grating.

MASTER DIFFRACTION GRATING vs REPLICA DIFFRACTION GRATING

In most cases the optical performance of a replica diffraction grating is virtually indistinguishable from the performance of the master from which it has been produced. There are very few applications that benefit from using a master grating instead of a replica grating.

Replica gratings are also generally lower in cost than master gratings (especially for volume production) and will exhibit better consistency from grating to grating.

Spectrum Scientific's proprietary blazing technique also means that our replica blazed gratings exhibit very high efficiency - especially in the UV - and significantly lower stray light compared to gratings produced using other types of blazing methods.



COATINGS

Diffraction gratings can be supplied with a number of different coating options depending on the application and wavelength range required.

For ultraviolet, visible, and infrared applications, aluminum coatings are generally used as they are more resistant to oxidation when compared to silver and offer better UV performance.

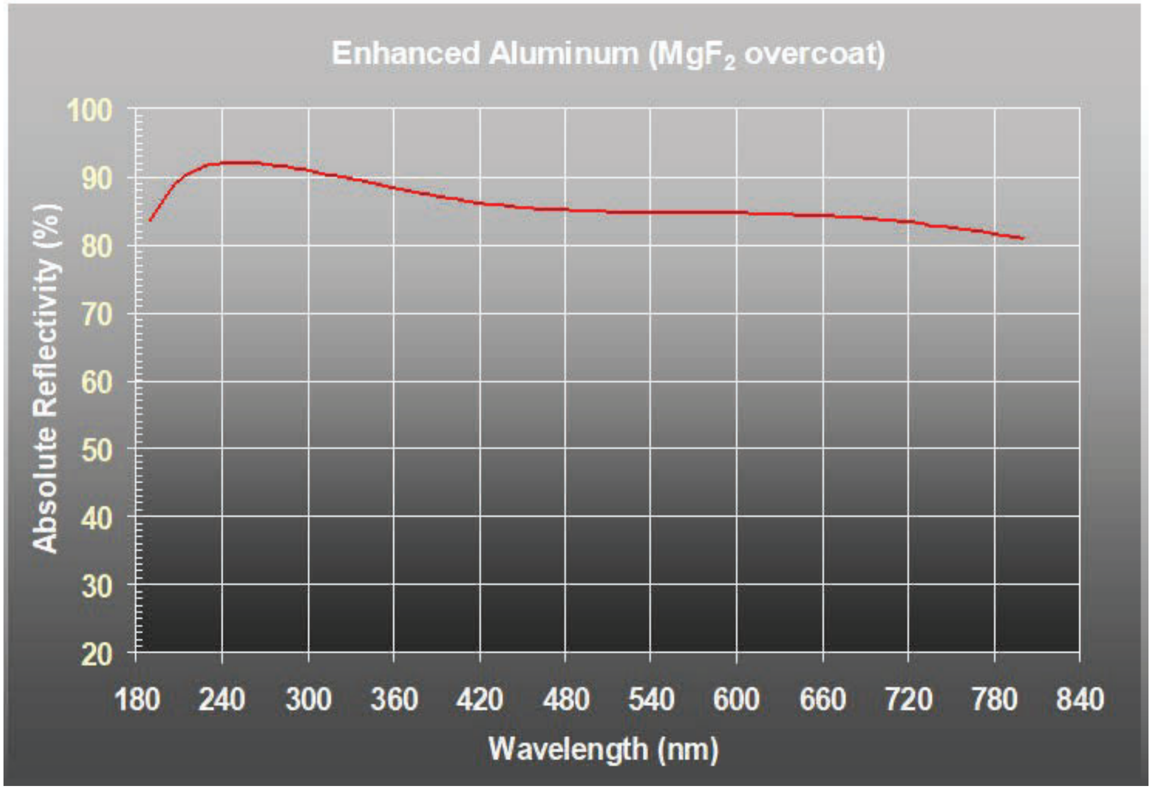
Aluminum averages greater than 90% reflectance from 200nm to the far infrared, except in the 750 - 900nm region where it averages around 85% reflectance.

Silver coatings can offer better performance in the visible and NIR from 450nm to 2µm.

For IR performance gold coatings offer high reflectivity of around 97% from 700nm up to 10µm.

Typical coatings supplied on diffraction gratings include:

- Bare aluminum
- Protected aluminum (with a MgF_2 or SiO_2 layer to protect the aluminum)
- Enhanced aluminum (a multi-layer film of dielectrics on top of the aluminum is used to increase the reflectance in the visible or ultraviolet regions)
- Protected Silver
- Gold for IR use (700nm to 10µm ~97%R)
- Specialist coatings such as DUV coatings down to 120nm are also available.



TYPES OF HOLOGRAPHIC GRATINGS

A holographic grating is a diffraction grating manufactured using a photolithographic technique that utilizes a holographic interference pattern.

Two intersecting laser beams produce equally spaced interference fringes that are projected onto a photoresist material on the grating substrate. The photoresist dissolves in proportion to the intensity of the fringes resulting in a holographic grating that has a sinusoidal profile.

The holographic grating is then coated with a reflective coating. Which typically may be aluminum, enhanced aluminum, silver or gold.

Because a holographic diffraction grating has no periodic errors or imperfections, it exhibits significantly lower stray light compared to a ruled grating, and no ghosting effects.

A holographic grating can be blazed to produce a blazed grating that has increased efficiency over a defined spectral region.

Sinusoidal Holographic Grating

A sinusoidal grating is a diffraction grating that has a sinusoidal groove profile where the grooves are symmetrical and have no blaze direction. They are commonly produced using interference lithography which results in a smooth groove surface and eliminates the periodic errors found in ruled gratings.

Typically, a sinusoidal grating offers a wider spectral coverage compared to a blazed grating but has lower efficiency.

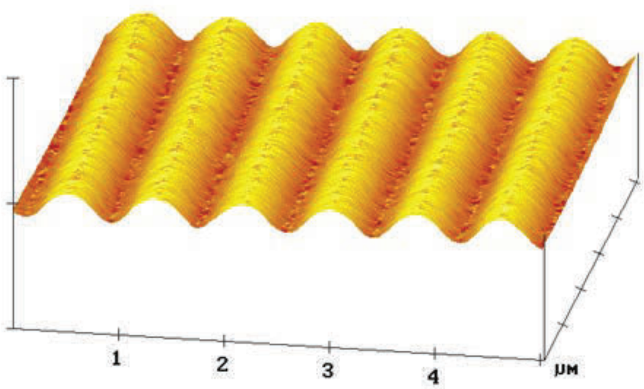


Figure 2: Sinusoidal grating profile

However, under certain conditions where the groove spacing and wavelength ratio are close to unity, a sinusoidal grating can exhibit the same efficiency as a blazed grating.

Blazed Holographic Grating

A blazed holographic grating is a diffraction grating where the sinusoidal profile has been transformed into a 'saw tooth' profile. This saw tooth profile effectively increases the efficiency of the blazed grating over the required wavelength region.

The blaze wavelength is the wavelength where the grating gives maximum efficiency. A blazed holographic diffraction grating can be manufactured using several techniques.

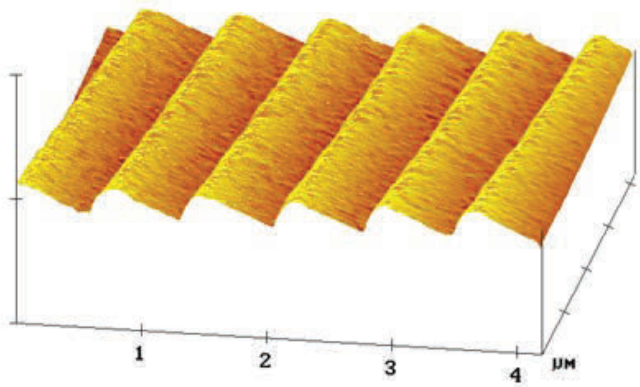
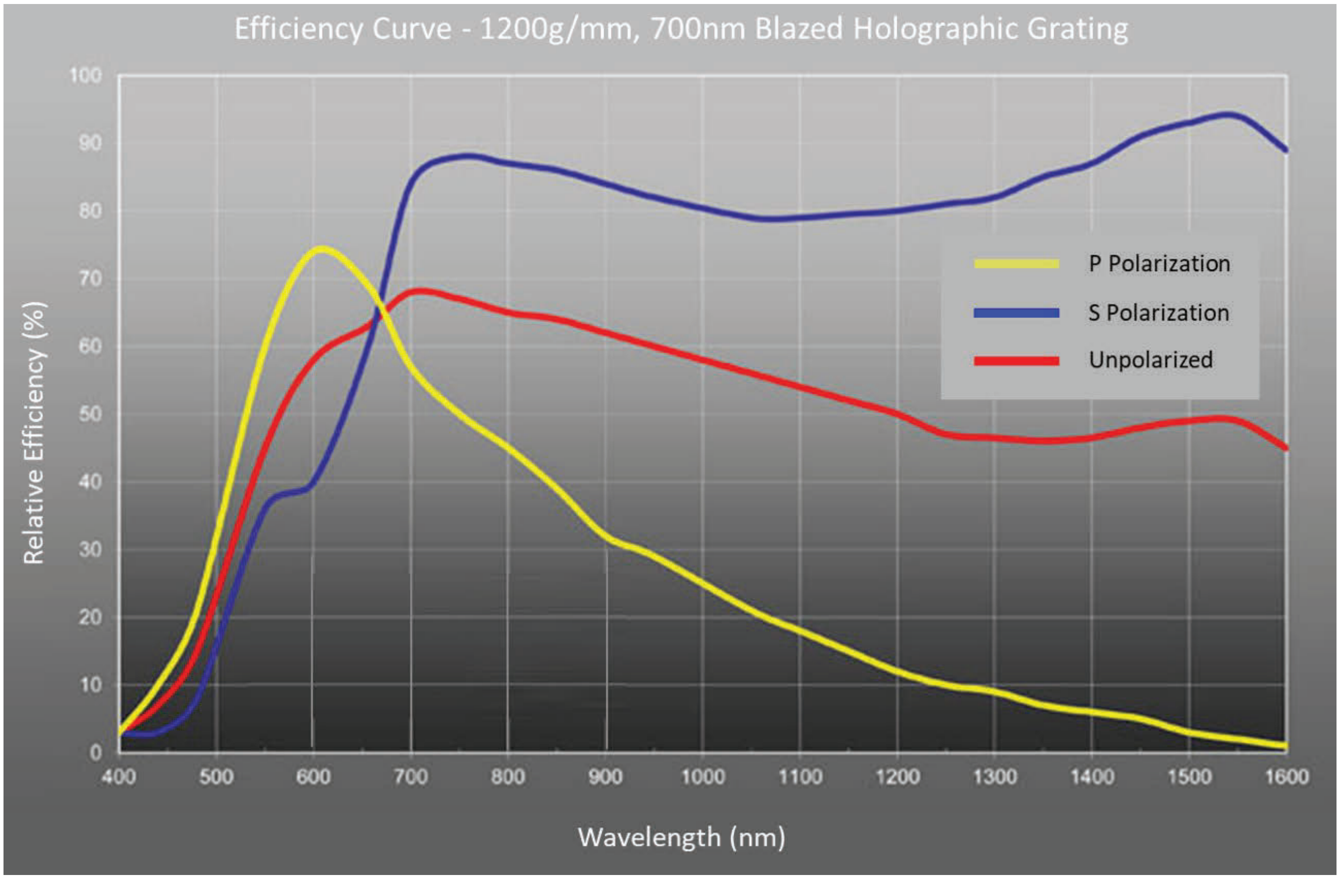


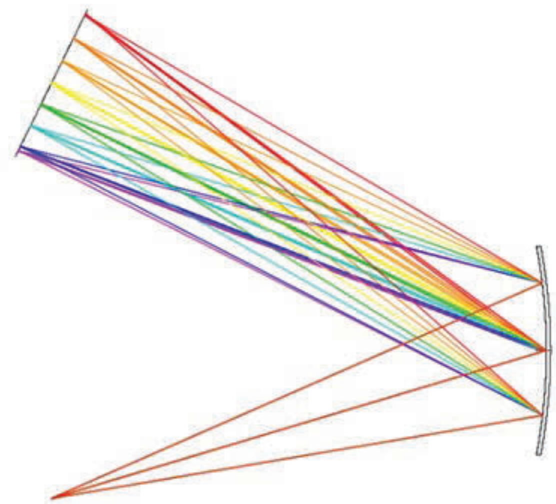
Figure 3: Blazed grating profile

Typically gratings are blazed using ion beam etching to create a saw tooth profile, however, Spectrum Scientific uses a proprietary technique that creates a blazed grating offering high UV efficiency and significantly lower stray light when compared to an ion-etched blazed grating.



A blazed holographic grating offers similar high efficiency to a blazed ruled grating, but with significantly lower stray light and no ghosting.

Concave Grating



The main advantage of a concave grating is that it can be used as the primary dispersive and focusing element in an instrument. The concave grating reduces the number of optical elements required, increasing throughput and instrument efficiency.

There are typically four types of concave grating.

- Blazed Holographic Concave Grating
- Aberration Corrected Flat Field Imaging Grating
- Constant Deviation Monochromator Grating
- Rowland Type Concave Grating

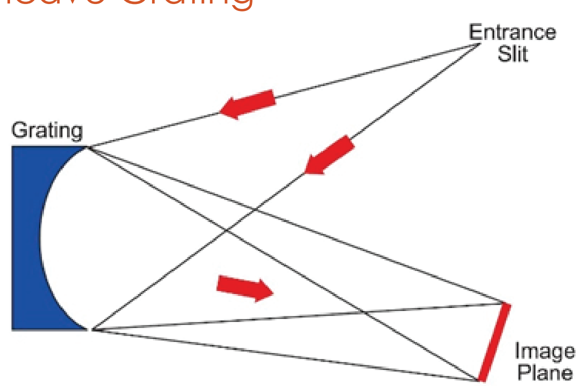
Blazed Holographic Concave Grating

A blazed concave grating is similar to a standard blazed grating where the groove profile has been modified to increase efficiency in a defined spectral region. Unlike some other types of blazed holographic concave gratings, the concave gratings produced by Spectrum Scientific are produced using a process that yields a blaze profile that varies across the grating surface, increasing efficiency across the full image plane. Typical efficiencies of >80% are achievable.

Aberration Corrected (Flat Field Imaging) Concave Grating

An aberration corrected concave grating (or flat field imaging grating) has grooves that are neither parallel nor equidistant and is designed to eliminate astigmatism and allow the complete spectral range to be imaged on a plane.

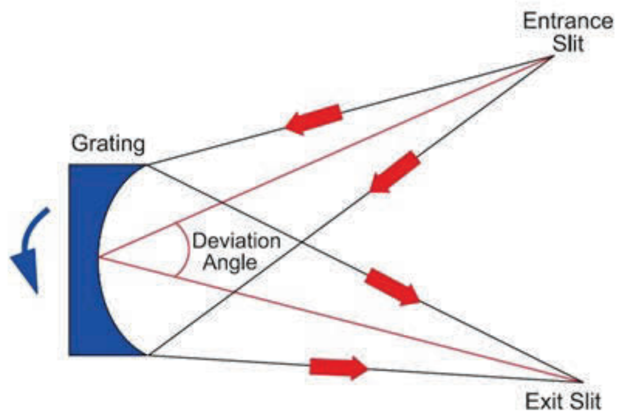
This makes an aberration corrected concave grating ideal for use with planar array detectors such as photo diode arrays (PDA) or charge coupled device (CCD) detectors.



Constant Deviation Monochromator Concave Grating

A constant deviation monochromator grating is a type of concave grating used in a scanning monochromator where the grating is rotated and scans the signal from the entrance slit across the exit slit. The deviation angle between the incident signal and diffracted signal remains constant.

The main advantage of a constant deviation concave grating over a plane grating is that it removes the need for collimating and focusing optics, reducing the number of optical elements and increasing throughput. It also allows more compact instrument designs.

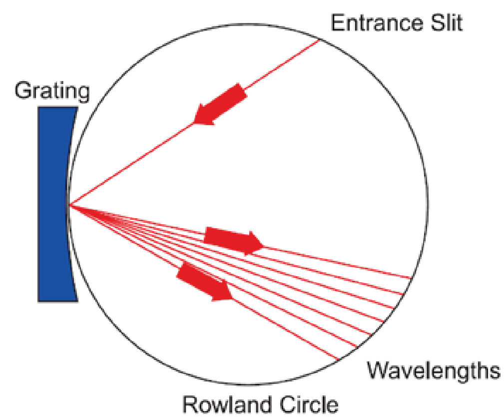


Rowland Type Concave Grating

A Rowland type concave grating is one where the grooves are straight and equidistant.

This type of concave grating diffracts the spectrum onto a Rowland circle which is defined as a circle where the diameter of the circle is equal to the radius of curvature of the concave grating.

Rowland type concave gratings suffer from astigmatism, but other types of aberration are small.



Pulse Compression Grating

A pulse compression grating is a special type of plane sinusoidal grating that is used for Laser Chirped Pulse Compression and typically optimized for use at 1053nm.

A pulse compression grating needs to have a very high damage threshold and high efficiency (>90% for Littrow incidence, S-polarization).

Spectrum Scientific, Inc.

Transmission Grating

A transmission grating is produced in the same way as a reflection grating, but the grooves are designed to diffract transmitted light. Transmission gratings offer high efficiency and are generally easier to align than reflection gratings. To produce high efficiency, a transmission grating usually requires a deep groove profile.

Transmission gratings are usually supplied with an antireflection coating.

Spectrum Scientific does not manufacture transmission gratings.

Telecom Grating

Modern telecommunications allow for vast amounts of information to be moved through optical fibers. Gratings allow for the management of the signals in the fibers by separating the individual wavelengths, allowing access to the information.

Telecom applications require gratings with very low polarization dependent loss (PDL) coupled with high diffraction efficiency. They also need to be highly environmentally stable with very good grating to grating repeatability.

about Spectrum Scientific

Spectrum Scientific, Inc (SSI) has been manufacturing high volume flat, aspheric and freeform reflective optics, hollow retroreflectors and holographic diffraction gratings since 2004.

We primarily use the optical replication process allowing us to supply high fidelity, high specification precision optics at a lower cost compared to traditional volume manufacturing.

One of our key capabilities is the manufacture of freeform optics, off-axis paraboloids and ellipsoid mirrors with surface figures down to $\lambda/10$ or better. We also manufacture plane, concave and convex holographic diffraction gratings, which can be supplied as blazed gratings using our proprietary blazing technique, which not only offers high efficiency in the UV, but lower stray light compared to conventional ion etched gratings.

Our high precision replicated optics, include spherical, freeform and aspherical mirrors (on or off-axis parabolic mirrors, elliptical mirrors, toroidal mirrors and cylinders) as well as retroreflectors, nanostructures, hybrid optics and complex optics.

Spectrum Scientific is ISO 9001:2015 certified and RoHS compliant and our production and test areas are space qualified offering a silicone free production environment where we can replicate off-axis-parabolic, ellipsoidal and freeform mirrors for space borne telescopes and optical interconnect systems.

We have supplied a number of ultra-low stray light gratings for a number of high profile projects, including the Orbiting Carbon Observatory (OCO) and Ozone Mapping Profiler Suite (OMPS).

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