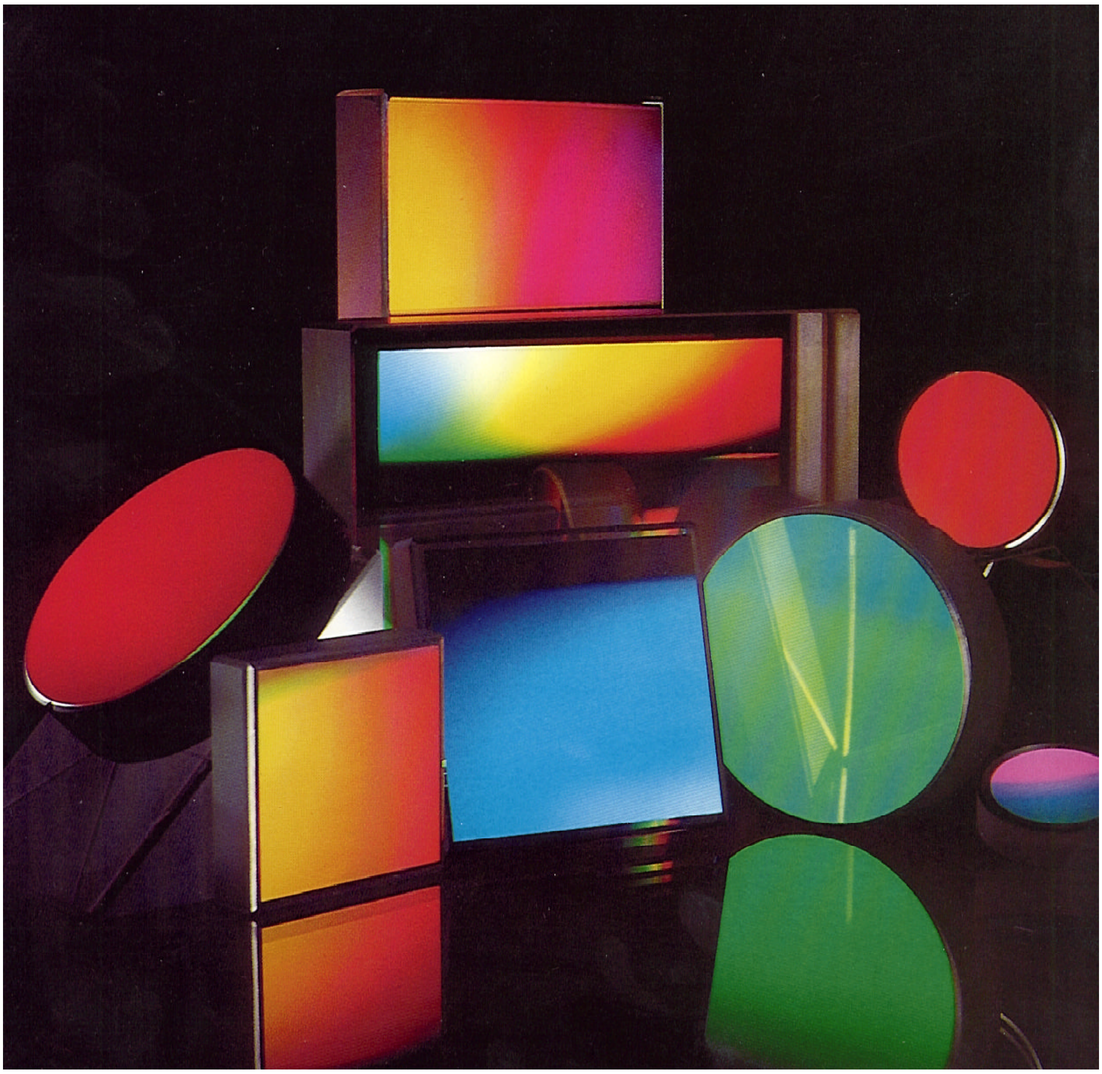
Spectral Sensors by Carl Zeiss

Mechanically Ruled Gratings
Holographic Gratings
Plane Gratings
Imaging Gratings



Mechanically ruled or holographically recorded - our gratings excel in precision and efficiency

High efficiency and minimum straylight
Customized production

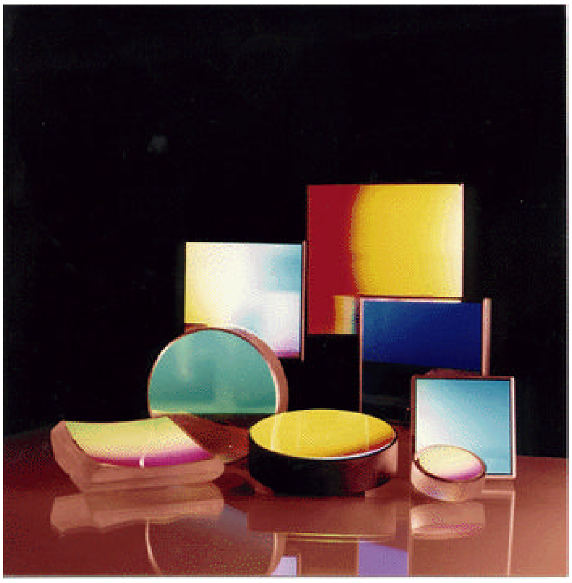


Figure 1:

Zeiss precision diffraction gratings are at the heart of monochromators, spectrographs, spectrometers, spectrophotometers, dye lasers and other laser types. They are most valuable in curricula, metrology and in solving special problems.

Many years of experience in the development and manufacture of diffraction gratings make Carl Zeiss for the right address of diffraction optics. The technical basis of production are holographic exposure systems and ultra-high-precision ruling engines which offer multiple possibilities of modification.

The benefits of holographically produced gratings are their high diffraction efficiency, even with high groove frequencies, and their very low straylight. Holographic procedures also allow the generation of asymmetric and symmetric groove profiles. Mechanically ruled Zeiss gratings distinguish by a particularly uniform groove spacing, resulting in low straylight. This ensures that spectrometers have a high detection sensitivity even for low-intensity signals and provide increased measurement accuracy in the visible and infrared ranges.

In addition to our standard line of gratings, we also produce customised gratings, allowing us to meet the critical demands made by quality-conscious users in spectroscopy and laser technology.

Carl Zeiss produces:

- Mechanically ruled plane gratings for the spectral range from 0.5 nm to 40 µm. Groove frequency 4 to 3000 grooves/mm.
- Holographically produced plane and · concave gratings for the spectral range from 150 nm to 5 µm. Groove frequency 40 to 6400 grooves/mm.
- Diffractive, holographically produced beam-shaping optics (HOE) for laser applications and beam splitter with a fixed and a variable splitting ratio, resonator gratings and collimators for laser diodes.

The classical production method

We produce a wide variety of high-quality gratings with three ruling engines. Its high mechanical precision is further increased by several orders of magnitude using an interferometric control system.

Echelette gratings with sawtooth groove profiles

The large groove faces of echelette gratings reflect most of the light in the diffraction direction determined by the groove spacing, i.e. the grating constant, a property which is termed the blaze effect. The wavelength of maximum grating efficiency, the blaze wavelength, is determined by the angle of the groove faces. This wavelength can be set as required in ruled gratings. The high-precision groove profiles of Zeiss gratings ensure a high efficiency over a wide spectral range.

Mechanically ruled gratings- virtually free of ghosts and straylight

Periodic errors cause grating ghosts which may be due to irregular operation of the ruling engine. The Zeiss ruling engines are interferometrically controlled which reduces the intensity of grating ghosts to a negligible minimum.
Random groove displacement or local deviations from the ideal profile shape, i.e. roughness, cause diffuse straylight. The choice of adequate metals for the ruled film, optimum production conditions, precise adjustment of the ruling process and the quality of the replication process keep diffuse straylight extremely low.

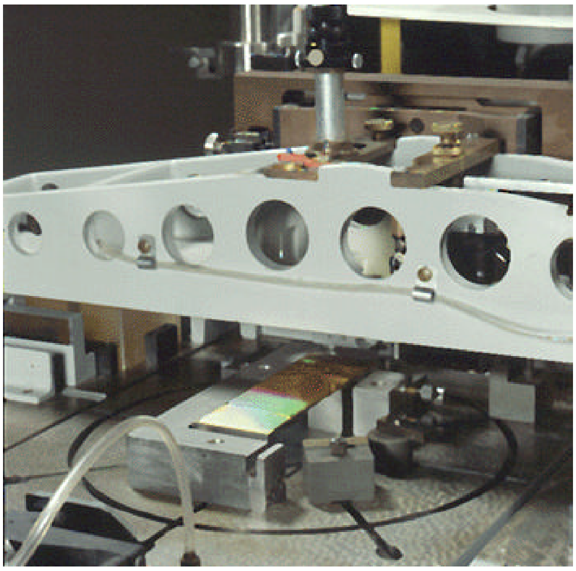


Figure 2: Mechanical ruling engine with an interferometric control system.

Resolving power near the theoretical limit

The theoretical resolving power of a grating is defined by the product of total number of grooves and diffraction order. It is approximately attained if the deviations of the wavefront diffracted by the grating are small compared with the wavelength used. High optical flatness of the blank and adequate freedom from systematic, periodic and random errors of the grating constant are required for this purpose. The surface quality of the substrate of Zeiss echelette gratings and the exceptional accuracy of the ruling engines fulfil these requirements.
Routine interferometric wavefront examinations in the second or higher diffraction orders guarantee the grating quality; the resolving power exceeds generally 80% of the theoretical limit.

The holographic production method

The holographic technique is used to produce gratings by recording the pattern generated by a fine laser interference field on a photoresist film.

It is not a new idea to use light itself for the production of gratings. Michelson published suggestions to this effect as long ago as 1915. The production of high-grade spectroscopic gratings, however, has become possible only with the availability of high-resolution photoresist films and lasers with shortwave emission wavelength.

On this basis, Zeiss developed new production technologies and the necessary equipment for the manufacture of holographic gratings which can be used in a wide range of applications. Holographic gratings have a low level of straylight and are totally free from ruling errors. Another benefit offered by these gratings is that special optical imaging properties can be realised which cannot be achieved using mechanical means, e.g. the correction of aberrations in concave gratings.

Thus, holographic gratings considerably extend the range of application of diffraction gratings. Whether a ruled or a holographic grating is the best choice for a specific application depends on the grating properties required.

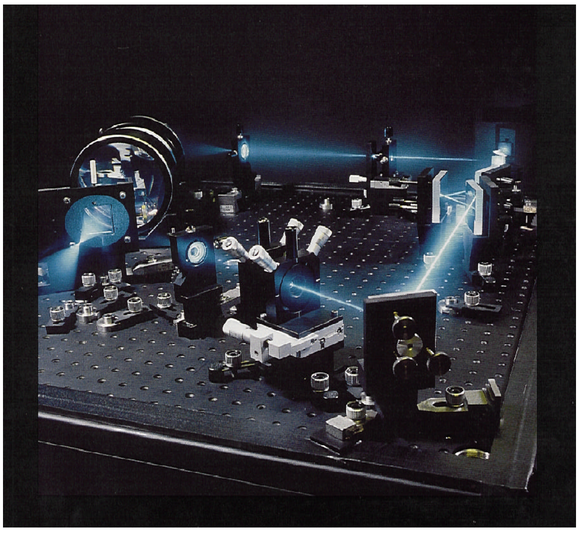


Figure 3: Interferometer setup and beam path for holographic exposure.

More performance at a lower price due to replication techniques

With a original replication technique developed by Zeiss, numerous replicas can be made of a master grating produced according to one of the aforementioned methods. The replicas have the same properties and quality as the master grating.

The replicating process allows the batch production of gratings, offering price advantages to users.

Zeiss subjects all diffraction gratings- mastergratings and replicas - to a most stringent quality control:

- Spectral efficiency and straylight are measured in a testing spectrometer.
- The diffracted wavefront, i. e. the resolving power, is checked interferometrically.
- The groove profile is checked using a light microscope and an Atomic-Force-Microscope. This is why Zeiss is able to guarantee constant high quality standards.

In addition, Zeiss offers technical consulting to realize and optimize your application case.

Diffraction gratings with symmetric groove profiles

Gratings with symmetric groove profiles are holographically recorded, free from ruling errors and show extremely low straylight. Special optical properties can be realised with holographic gratings, which cannot be achieved mechanically, e.g. the aberration correction of concave gratings. Furthermore holographic gratings are easy to produce in cases where mechanical ruling requires more effort, e.g. if the ruled areas are large and the groove density is high.

Theoretical efficiency almost achieved

High efficiency is also obtainable with symmetric groove profiles, provided the grating constant d is small compared with the wavelength lso that the higher orders of diffraction are cancelled and all energy is concentrated in the zero and first orders. The optimum working range of symmetric gratings is thus given by $\lambda/d >= 0.67$.

The higher the groove density, the more the efficiency curves of the gratings shift towards shorter wavelengths.

Zeiss optimised the groove profile of holographic gratings so as to virtually suppress even the zero diffraction order. The extraordinarily high efficiency of such gratings equals that of ruled echelette gratings or rather by using polarized light the efficieny is quite better.

Ionbeam etching of holographic gratings

In ionbeam etching, the grating grooves in the photoresist coating are transferred to the blank surface. This increases the mechanical and thermal stability of the master gratings, permitting their use in UHV spectral units. There are two methods of groove transfer: the true-to-shape transfer of grooves where the original shape of the profile is retained, and the shape-modifying transfer of grooves where, especially in reactive ionbeam etching, the shape of the profile is deliberately changed. This makes it possible to manufacture aberration corrected concave gratings with good blaze properties for the spectral range from soft X-radiation to the infrared. Ionetched laminar gratings with a rectangular profile show extremely low straylight, as the low microroughness of the blank surface is retained on the groove surfaces during the manufacturing process.

Specific advantages of gratings with high groove densities:

- Higher diffraction orders are cancelled. For this reason, these gratings offer the largest possible free spectral range. Order filters or predispersers are generally not necessary.
- Sufficient distance between spectral lines and because of that precise wavelength selection due to high dispersion.
- In autocollimation, the diffraction angle is between 20° and 60°. For this reason, the resolving power in the first order is as high as in the higher orders obtained with echelle gratings. The repeated order change typical of echelles is not necessary; in addition, efficiency is higher over a wide spectral range.
- The light throughput of the units in which the gratings are integrated can be considerably increased, as much larger slit widths can be used without any loss in resolving power.

Zeiss laser gratings for all types of dye lasers

Holographic gratings are the best wavelength selectors for dye lasers. Zeiss laser gratings offer the high efficiency and high dispersion required for polarised laser beams and are successfully used in all types of dye lasers.

CO_2 laser gratings

Mechanically ruled gratings are used in lasers, if a high efficiency is required or if the grating is subjected to high thermal exposure. Carl Zeiss produces mechanically ruled gratings on BK7, ZKN 7, Zerodur, silicon, copper,molybdenum and steel blanks for different laser powers. The absolute efficiency attained for CO_2 laser gratings, for example, is higher than 97%.

Moderately priced gratings for curricula and demonstrations

Transmission and reflection gratings are available with and without blaze effect. They are supplied in slide format including a coverglass and in various other versions.

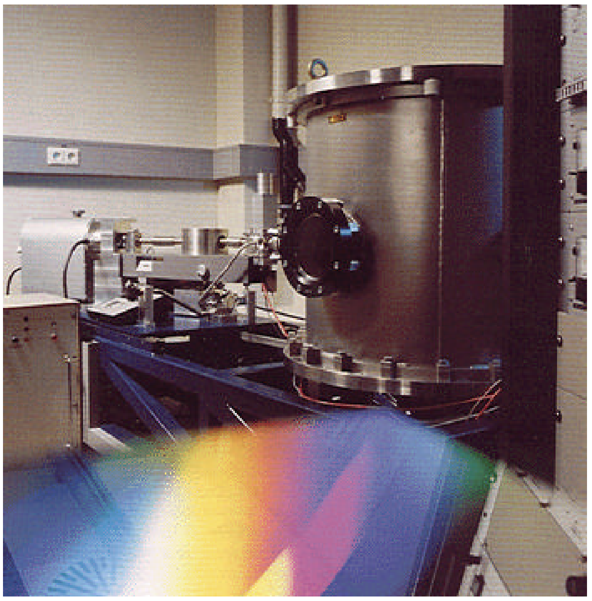


Figure 4:
Efficiency test station for UV. Vacuum chamber, monochromator and light source.

Diffracted wavefront highly flat

Zeiss uses interference fields of high homogeneity to record holographic gratings on blanks whose flatness is always better than λ/4. This flatness is fully retained during the entire production process due to a special coating process.

Interferometric testing ensures that wavefront aberrations are always below λ/4, resulting in maximum resolving power of the gratings. Each and every one of which is checked if necessary.

Holographic gratings -minimum straylight and freedom of ghosts

Due to the production technique used, holographic gratings show neither periodic nor random ruling errors. Zeiss holographic gratings are free of ghosts and their straylight intensity lies clearly below that of the best mechanically ruled gratings.

Concave gratings

Gratings with imaging properties for modern dispersive systems

Zeiss produces concave gratings holographically. The radii of curvature available are finely graded within a wide range. Relative apertures of as wide as 1:1 are obtainable. Concave gratings combine the dispersive properties of plane gratings with the imaging properties of concave mirrors. The spectrum is produced without auxiliary optical means. Aberrations, especially astigmatism, occur as in image formation with concave mirrors. Because of an aspheric surface production of its own, Zeiss is able to offer gratings also on toric, elliptic or other aspheric surfaces which show fewer aberrations than conventional concave gratings.

Aberrationcorrected concave gratings with considerably reduced aberrations

Aberration-corrected concave gratings are recorded in an interferometer set-up adapted to the potential use of the grating. As with holograms, this ensures aberrationfree images at the operating wavelength required. Astigmatism is completely compensated for specific wavelengths and also considerably reduced over a wide wavelength range. This permits the use of high-aperture gratings with large diffraction angles, resulting in particularly effective dispersive systems.

Cost advantages due to simple spectrometer design

- With corrected concave gratings it is in contrast to the classical Rowland gratings possible to vary the position of the focal curves in a wide range. From it novel simple versions of the optical design of dispersive systems can follow.
- Monochromator arrangements consisting only of a fixed entrance and exit slit and a grating rotating around its axis.
- Spectrometers of the polychromator type without movable parts, with a fixed grating and a flat diode array covering all wavelengths of interest.
- Spectrographs with a fixed entrance slit, fixed grating and e.g.a camera with considerably reduced astigmatic deformation of the spectral lines
- Even in classical arrangements, e.g. with entrance and exit slits on a Rowland circle, aberrationcorrected gratings can be used to best advantage.

Your benefit from these advantages

- The aberration correction of holographic concave gratings guarantees high resolving power and small bandwidths even at high apertures
- Dispersive systems of high light- gathering power and compactness can be implemented using gratings with wide apertures. The light-gathering power is further increased by the high efficiency of the Zeiss holographic gratings
- Straylight is considerably reduced by simple design using fewer scattering surfaces. Less astigmatism allows the use of smaller slit diameter with reduced transmission of straylight. Zeiss holographic gratings are virtually straylight-free
- Cost advantages due to the elimination of collimating and other imaging components and the use of a simplified mechanical system including easy adjustment

Imaging Gratings

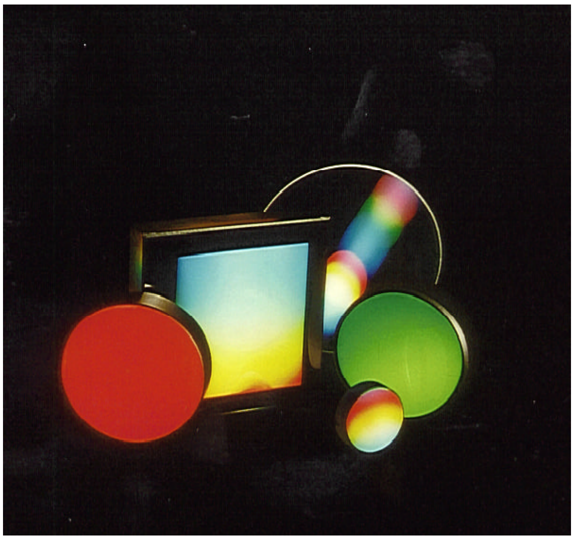


Figure 5:

Holographically corrected concave gratings

Concave diffraction gratings combine both dispersive and imaging properties, making them ideal for use in modern spectroscopic systems. The number of optical components of these systems is low: this reduces straylight and increases the light throughput on the one hand, and on the other, it also guarantees clear and compact design and simplified operation. The basic form of all imaging gratings is the Rowland circle grating. Its application-specific feature: the entrance slit, the grating and the detector must be positioned on the diffraction circle of the Rowland grating, the Rowland circle. The Rowland circle configuration allows coma-free imaging and ensures high spectral resolution despite astigmatic elongation of the slit image. Due to its curved focal plane, the Rowland circle configuration is, however, not suitable for use in monochromators or flat-field spectrometers. Holographically corrected exposure of concave gratings can both optimize the focal plane and minimize aberrations, such as astigmatism, spherical aberration and coma, over a wide spectral range. Unlike Rowland circle gratings, these aberrationcorrected gratings exhibit grooves with a variable spacing and variable curvatures. This holographic design allows optimum adaptation of a grating's imaging properties to the specific requirements of the spectral unit in which the grating will be used .This ensures that gratings are obtained whose imaging properties effectively concentrate the available light energy on the detector over a wide spectral range. Holographically corrected gratings are ideal for imaging the spectrum on a diode array or a CCD sensor. It is therefore possible to produce modern, compact high-resolution spectrometers and spectrometer modules at justifiable cost.

Applications

Imaging gratings for monochromators

In monochromators with their fixed entrance slit, grating vertex and exit slit, the focus of conventional gratings moves out of the exit slit plane with increasing spectrum length. Holographic correction can largely suppress this aberration and markedly improve resolution.

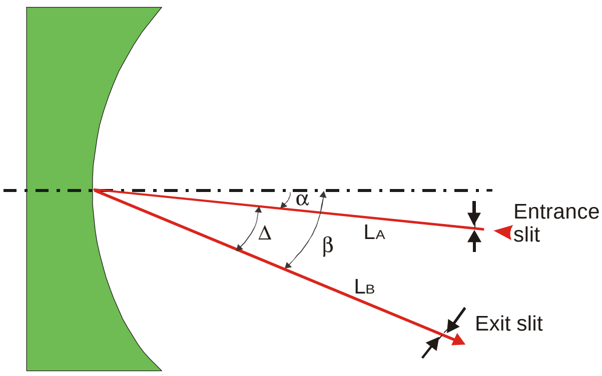


Figure 6:

Imaging diffraction grating in monochromator setup

The simultaneous suppression of astigmatism and coma in the range specified is a criterion for the quality of holographic design.

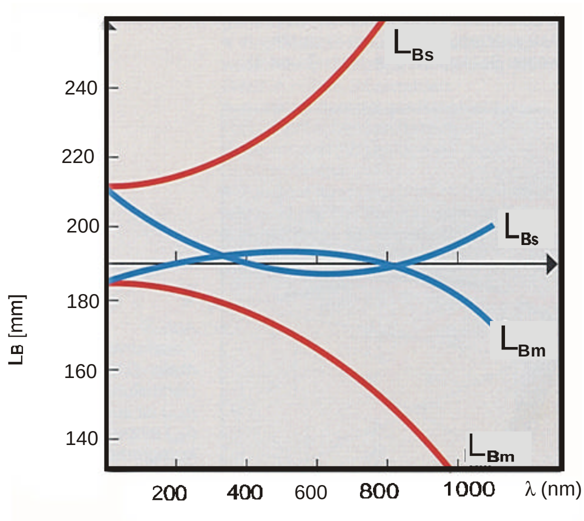


Figure 7:

Focal curves (blue) of a corrected monochromator grating in comparison the uncorrected focal curves (red).

Specifications of standard gratings	
Groove frequency	150 - 1900 L/mm
Spectral range	190 - 2500 nm
Focal lengths	50 - 300 mm
Relative apertur el/D	≥1,6
Types of grating	Sine, echelett- and laminar
Monochromatic straylight	≤ 2×10^{-5} degree $^{-2}$ (depending on wavelength)

Applications

Imaging gratings for diode array spectrometers

In diode array spectrometers, the entrance slit, the diffraction grating and the diode array are fixed. For this reason, they require diffraction gratings which image the entrance slit on the plane diode array. This requirement cannot be met by classical Rowland circle gratings. Unlike these gratings, however, holographically corrected gratings with unequal groove spacing can be designed to obtain an almost straight focal curve. In addition, astigmatism and coma can also be corrected over a wide spectral range.

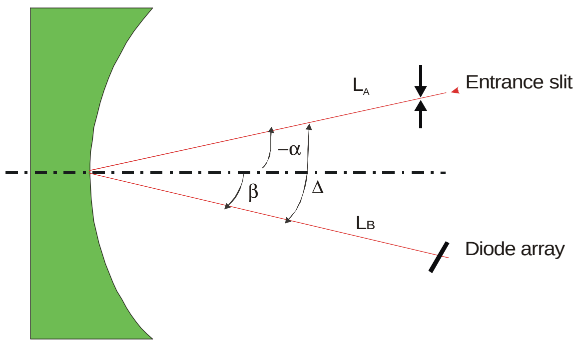


Abbildung 8:

Imaging diffraction grating in spectrometer setup

Specifications of standard gratings	
Groove frequency	100 - 2600 L/mm
Spectral range	190 - 900 nm
Focal lengths	20 - 200 mm
Relative aperture f/D	≥1,6
Types of grating	Sine, echelette and laminar
Monochromatic straylight	$\leq 2 \times 10^{-5}$ degree $^{-2}$ (depending on wavelength)

Holographically corrected gratings

The production of holographically corrected gratings requires the use of:

- sophisticated grating design program for matching the imaging properties to the application intended and distributing the diffraction efficiency across the spectrum
- optical components for the holography set-up which meet the critical demands made on wavefront accuracy and cleanliness
- holography set-ups with a very high stability and alignment accuracy
- high-precision machining of the grating blanks
- reproducible photoresist techniques for groove generation with nanometer accuracy
- replication technique for the precise and economical manufacturing of gratings in production quantities
- vacuum deposition technology to obtain guaranteemaximum reflection and a low level of straylight of the gratings
- sophisticated testing technology which ensures that optimum properties are obtained during the production process.

Interferometric set-ups

Unlike the conventional exposure procedure using plane waves, two spherical waves, partly with specific aspheric deformation, are made to interfere in the photoresist layer on the blank to generate holographically corrected gratings. For this, two interferometer set-ups are primarily used (Figs 9 and 10).
The principle illustrated in Fig. 9 is employed to produce gratings with a symmetrical groove profile (sinusoidal and laminar gratings). These gratings offer a high level of efficiency in the spectral dispersion of light over a wide range of wavelengths.

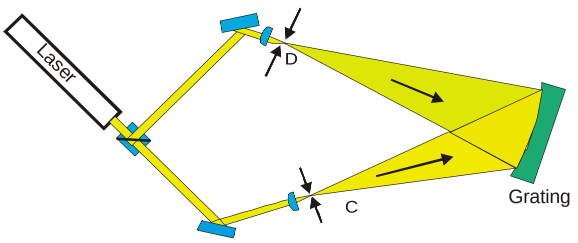


Figure 9:

Generation of concave gratings with symmetric groove profile
C and D are the sources of spherical waves

Holographically corrected gratings

The principle illustrated in Fig.10 is taken as a basis to produce gratings with sawtooth-shaped groove profile (often been termed echelettes or blazed gratings) having specially high efficiency in a specific wavelength range.
In exposure, the two interfering waves strike the photosensitive resist from two opposite directions resulting in a steep inclination of the nodal and antinodal planes of the interference field. During the development proce, the removal of the material continues along the antinodal planes, with the nodal planes as barriers. After a specific development time, the groove profile assumes the desired sawtooth shape.
To prevent grating ghosts and straylight, an antireflecting coating is vacuum-deposited on the grating blank back being passed through the convergent exposure wave.

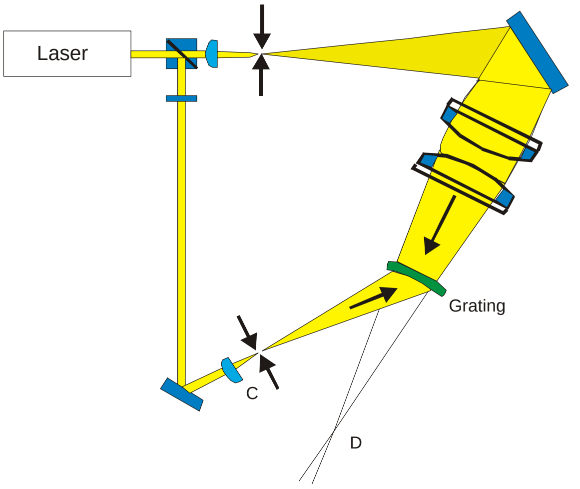


Figure 10:
Generation of concave gratings with sawtooth-shaped groove profile
C and D are the sources of spherical waves

Ionbeam etching

To improve the optical properties of blazed gratings, Carl Zeiss also uses ion-beam etching technology:

- Gas ions which are accelerated in an electric field strike the grating surface after collimation.
- They etch away the surface until the grooves have been transferred into the surface of the blank.
- It is also possible to deliberately change the groove profile, for example, to shift the · blaze wavelength of blazed holographic gratings to the spectral range required (e. g. from VUV to IR).

Sinusoidal gratings

Sinusoidal gratings have a symmetric groove profile. Gratings with groove frequencies and groove depths for use over wide range- from -VUV to IR - can be produced by selecting suitable process parameters, such as the angle between the interfering waves, and the exposure and development times.The groove depth and number of grooves determine the efficiency for the spectral range in which the grating can be used. (Definition grating constant d: distance between the grooves).
As in plane sinusoidal gratings, high efficiency in the region λ >=0.7xd can be attained in imaging sinusoidal gratings for light polarised normal to the groove direction. (Fig.11)

Fig.12 compares the spectral efficiency of unpolatized light diffracted by gratings with different groove profile.

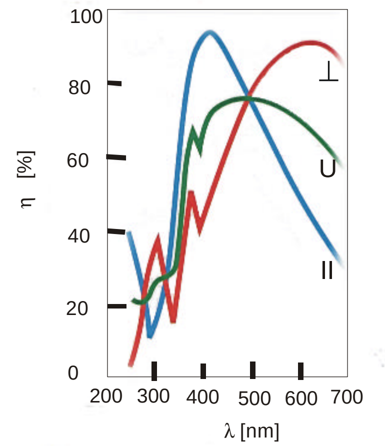
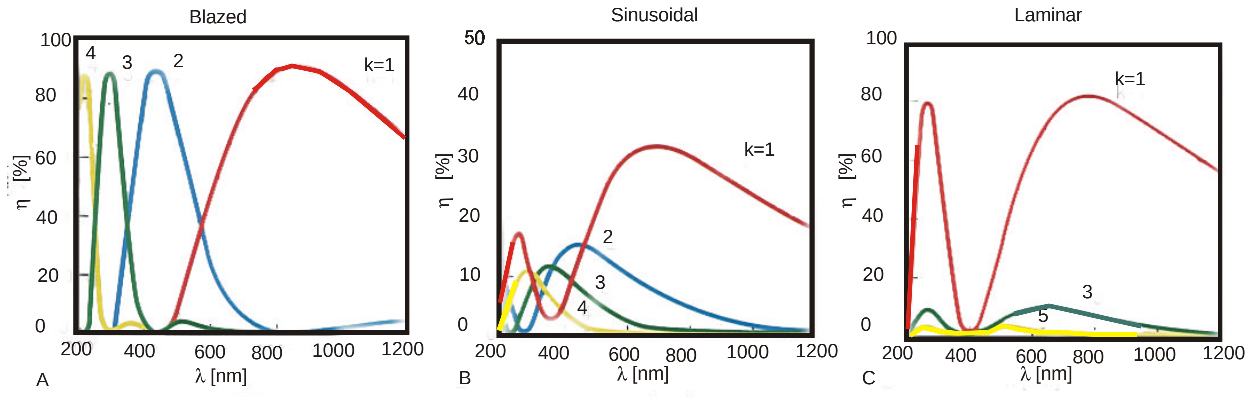


Figure 11:

Spectral efficiency curves of a sinusoidal grating with 1,830 grooves/mm, measurednear autocollimation (Δ = 3°)for unpolarized light (U) and light polarized ⊥ and // to the groove direction.

Figure 12:

Computed spectral curves of the relative efficiency η for different diffraction orders k in the scalar domain ($\lambda \leq 0{,}6d$).
The low efficiency in the high diffraction orders provided by the laminar gratings make this type of grating ideal for applications in which the superposition of the spectrum by higher diffraction orders would be annoying.



Laminar gratings

A variant of the sinusoidal profile is the laminar profile. Its rectangular shape is described by the groove depth and the land-to-groove ratio. The advantage of this type of grating over sinusoidal and echelette (blazed) gratings mainly consists in its ability to suppress higher diffraction orders whose efficiency can be influenced and minimised by varying the land-to-groove ratio . In grating production, the developing process is continued until the photoresist has been removed as far as the blank's surface and glass strips are uncovered corresponding to the land-to-groove ratio. In a subsequent ionbeam etching process, the strips exposed are etched off until the groove depth required has been obtained. The photoresist strips masking the lands during this process are then removed from the grating surface.
Laminar gratings produce a markedly lower level of straylight than comparable sinusoidal and blazed gratings: on the one hand, the top surface of the groove profile retains the high quality of the blank's polished surface; on the other, the ionbeam process is conducted in such a way that there is no noticeable increase in microroughness, even when large etching depths are required, as in the case of IR gratings.

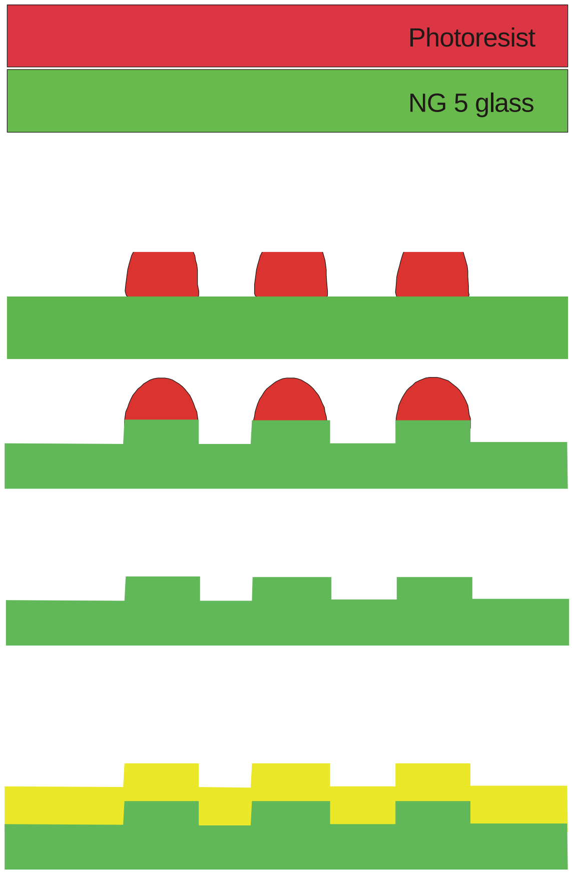


Figure 13:

Generation of a rectangular profile for laminar gratings by means of ionbeam etching

a) photoresist coating on blank

b) holographic exposure and photoresist development of grooves with a semi-sinusoidal profile

c) ion-beam etching

d) removal of remaining photoresist

e) application of a reflection coating

Replication

The work and time involved in the production of holographic master gratings are considerable. A sophisticated replication technique is used to allow the production of attractively priced gratings.

- The holographically produced grating patterns are first replicated on so-called daughter replicas.
- These are used to make a large number of „granddaughters“ (Fig. 1); the groove profile of these replicas corresponds to that of the master.

The reproducibility of accuracies in the nanometer range allows the production of replica gratings, the optical properties of which equal those of the master grating

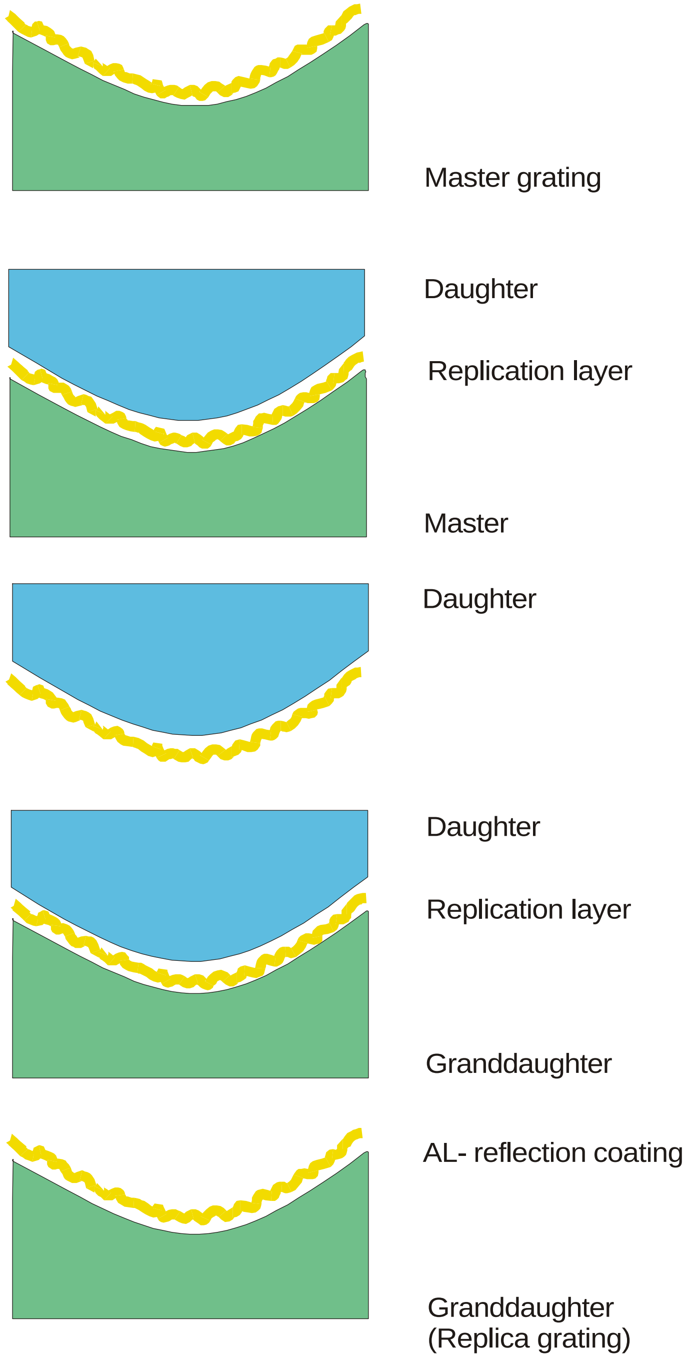


Figure 14:

Schematic illustration of a two-stage replication process: from the concave master via a convex daughter replica to the concave granddaughter grating (final replica)

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