Optical Gratings

Compendium of principles, manufacture, products and applications

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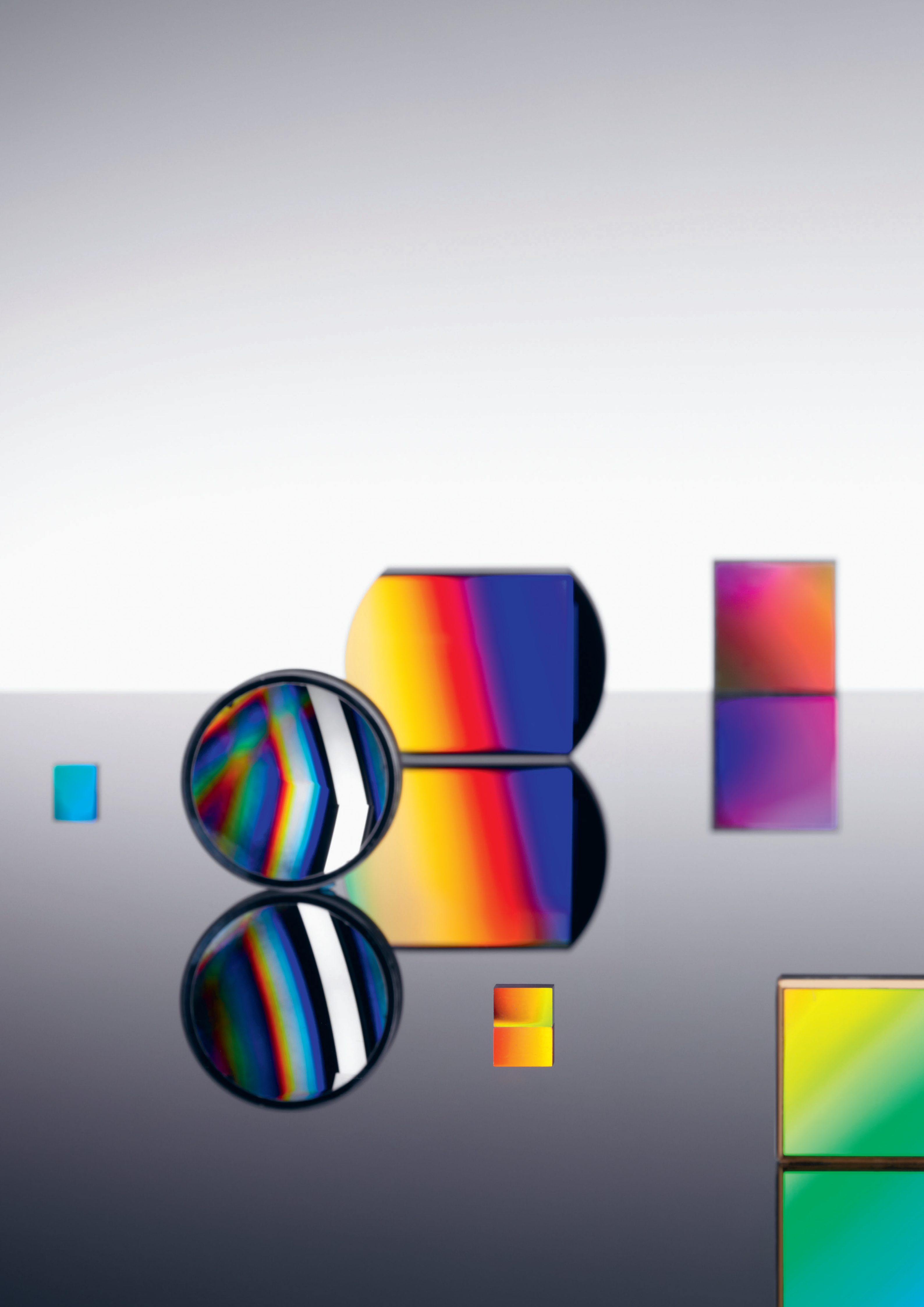

Optical gratings – perfectly ZEISS

In 1821 Josef Fraunhofer (1787–1826) was the first scientist to conduct experiments on the diffraction of light on optical gratings which he virtually "rediscovered" for this purpose. The American astronomer David Rittenhouse (1732–1796) had already produced the first grating with a four-slit arrangement as far back as 1785. In 1882 the gratings, which were produced by mechanical means only (Fraunhofer himself used wires), were decisively improved by H.A. Rowland (1848–1901) in terms of the degree of precision that they offered. In addition to the theoretical discoveries in the field of physics made during this period, he also initiated new developments in the application of gratings. To this very day, however, the production of mechanically ruled gratings is still extremely time- and cost-intensive and requires the ultimate in precision engineering skills.

The first grating ruling engine for 30 x 30 mm gratings was probably set up in a design office at ZEISS in Jena around 1925. The first verifiable record of a grating ruled at ZEISS dates back to 18 January 1938. This was the day when the 101st ruling was performed by a modified Rowland-type ruling engine. After the end of World War II in 1945, and the subsequent partition of Germany and ZEISS, many products were developed in parallel in the two ZEISS companies in West and East Germany. And this also applied to grating manufacture in the decades to follow. During the 1950s, the first endeavors to set up grating production facilities were made in both Jena and Oberkochen as the first ruling engine was no longer available.

In Jena a new grating ruling engine (GTM I – Rowland type) was developed in 1951. This GTM I featured two all-time firsts: the moving slides were supported by an oil pressure mount, and the stepping switch mechanism used a smooth stepping disk instead of a gearwheel. At the end of 1955 a reproducible relative diffraction efficiency of ≥ 70 % in the maximum on a diffractive area of 70 x 64 mm² was achieved for gratings with 651 L/mm ruled by the machine applying this stepping disk.

In 1955 the Oberkochen facility also began to set up ruling technology and construct ruling engines for diffraction gratings displaying a ruling length of 75 mm.

In the 1960s and 1970s the potential for producing mechanical master gratings was expanded at both ZEISS companies through the use of additional ruling engines. The improvements and innovations of the ruling engines built in Jena allowed the parallel ruling of up to 4 gratings, the production of gratings with a small groove density for the infrared range and of grating prisms (GRISMs). The produced gratings displayed a maximum diffraction efficiency of approximately 90 %. The vibration sensitivity of the last generation of ruling engines was so low that they no longer made any contribution to stray light.

With the ruling engines set up in Oberkochen it was possible to further increase the size of the ruled grating surface. Here, the first interferometric control of the ruling arm was also used, allowing highly precise spacing of the grating lines in order to minimize the stray light caused by "grating ghosts". The two ruling engines used today produce mechanically ruled gratings which embody the know-how and expertise of ZEISS in the field of precision engineering and represent the state of the art in industrial production.

After 1950 there was a constant increase in the demand for plane gratings for monochromators. In response to this need, ZEISS initiated the development of replication technology for gratings, parallel to the ongoing development of the ruling engines. Without any compromise in efficiency, this technology makes it possible to produce precision grating replicas with a very low level of stray light that reproduce the flatness of the master gratings. ZEISS is one of the few quality providers in this field.

The company's own internal development of ion gas lasers in Jena during the 1970s was accompanied by the development of a special type of gratings known as holographic gratings which are produced by using optical interference methods. Right from day one, scientific research and engineering work were sharply focused on customer needs. This close collaboration ensured that rapid advances were achieved in the development, leading to extremely effective solutions. The mid-1970s saw the start of work on the production of holographic blaze gratings and the development of patented replication techniques. Blaze grating replicas and widefield gratings have been produced in series since 1980.

The dry etching technique used in Oberkochen for grating production in the early 1980s enabled the manufacture of gratings with extremely low stray light. The 1980s were marked by the increased development of holographic concave gratings.

After the reunification of the ZEISS plants in Oberkochen and Jena the know-how was gradually consolidated in the 1990s. The production of industrial grating replicas has been performed solely in Jena since the start of 2000. Until 2011, Oberkochen and Jena operated independent master grating production facilities, with Oberkochen concentrating on special gratings for synchrotron and space applications. These activities culminated in the production of, for example, the gratings for the James Webb Space Telescope in Oberkochen.

Today, ZEISS offers mechanically ruled plane gratings as well as holographically produced plane and concave gratings at the highest quality level. The standard program includes the production of precision replicas and specially manufactured master gratings.

ZEISS offers all customers collaborative assistance in the development of specific grating solutions. This incorporates the entire know-how and expertise of ZEISS, all garnered over many decades of scientific and engineering work and all at the customer's fingertips.

The moment you find proof that only partnership can lead to conclusive solutions.

This is the moment we work for.

// OPTICAL GRATINGS
MADE BY CARL ZEISS

Optical gratings – perfectly natural

Fig. 1

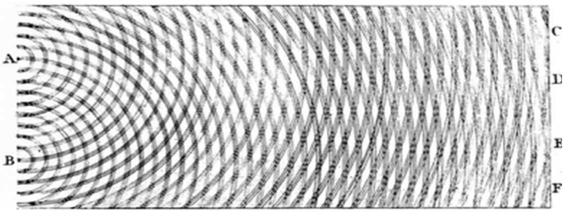

Fig. 2

Everyone has come into contact with optical gratings at some stage of their lives. Some people even have something to do with them every day without noticing that they are, to a certain extent, perfectly natural.

"Look at the sun through a feather or a black silk ribbon by holding it close to your eye. You will be able to see different stripes in the colors of the rainbow." The Scottish mathematician and astronomer James Gregory (1638–1675) used this method to discover the separation of sunlight into its various color components in 1673. He passed sunlight through a bird feather and used the barbs (Fig. 1) as an optical transmission grating.

Diffraction

The term "diffraction" was coined by Francesco Maria Grimaldi (1618–1663). The Italian physicist was the first person to discover that the incidence of light on a surface is no longer perpendicular once it encounters an obstacle along the way. In a dark room he held up a rod to the light and saw that the shadow of the rod was wider on a white surface than would have been expected from its geometrical shape.

In addition, fringes of one, two and three colors were visible at the edge. This effect can be described by the Latin word "diffringere", which means to break up or shatter. Later, Thomas Young (1773–1829) provided the wave-optical explanation for Grimaldi's observations (Fig. 2). Against this background, in 1785 David Rittenhouse succeeded in implementing gratings by using an arrangement of multiple slits or apertures, marking the first fundamental step in demonstrating the propagation of light in the form of waves.

Optical diffraction gratings in theory

A diffraction grating is a repeating sequence of evenly spaced diffraction elements, the gaps and

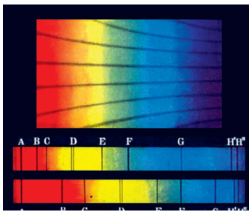

Fig. 3

Fig. 4

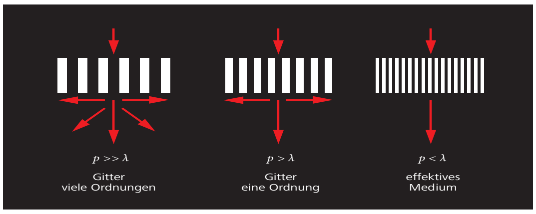

Fig. 5

the ridges which, in fixed alternation, influence the phase or amplitude of the incident light. Depending on the light's angle of incidence, rainbow-colored patterns are then discernible on a projection surface behind a transmission or reflection grating. The colored patterns are known as the optical spectrum.

Figs. 3 and 4 show examples of optical spectra. In Fig. 3 interference fringes in a spectrum and Fraunhofer lines in a prism spectrum and grating spectrum can be seen. Fig. 4 shows a candle flame surrounded by several spectra that are generated by a crossed multiline grating.

Optical spectra can be observed because the diffraction angle is dependent on the wavelength of light. For a given grating, light with a longer wavelength generally exhibits a larger diffraction angle. To be more exact, a single wavelength may simultaneously display several discrete diffraction angles, which are known as diffraction orders. This means that a grating separates an incident polychromatic ray into its constituent wavelength components and is therefore said to be dispersive. The diffraction order is a dimensionless number that counts the quantity of refracted sub-bundles, starting from the position of the zero ray.

Fig. 4 shows that successive higher orders may overlap: The higher the spectral order, the greater the overlap with the next order. The overlapping of orders results in the spectral line of the first order displaying exactly the same position as the spectral line of the second order with half the wavelength. The non-overlapping wavelength range of any order determine the free spectral range of a grating. The correlation between grating constant p and the number of the diffraction orders is illustrated in Fig. 5.

Groove density and line density are often used as synonyms for the grating constant. The line term originates in the field of linear measurement in precision technology and is used to describe any resolution in the unit of line per millimeter. dpi (dots per inch) is also a known as a measure of the quality of spatial printing or video dot density.

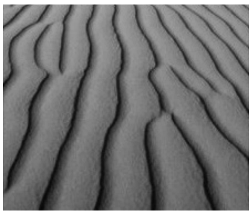

Fig. 6

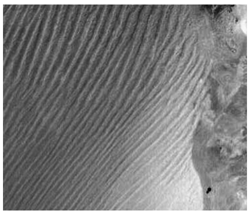

Fig. 7

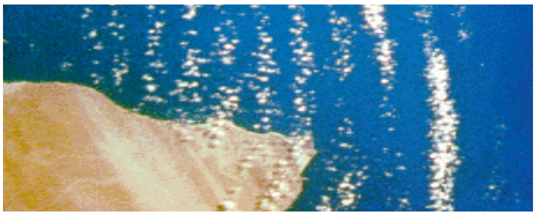

Fig. 8

Parallel lines

A line is a geometric figure that emerges from a point and moves in a fixed direction away from it. Lines and arrangements of parallel lines can be de described as the elemental form of structure. Arrangements of regular lines occur in inorganic and organic nature. Apart from three-dimensional crystal lattices in inorganic nature initially coarse gratings attract attention.

Fig. 6 shows the grooves on a sandy beach. These are undulating surfaces on striation layers. This clearly is a fine example of self-organization in nature as the lines bifurcate at two points. The spacing between the grooves is in the range of around ten centimeters. Fig. 7 shows the large sand dunes in in Saudi Arabia. They can be up to 100 km long, and the grooves spacing can vary between ten meters and several kilometers.

Regular line structures can also be discerned in the sky. These thin bands of clouds were identified as geographic features by various space shuttle crews. At certain times of the year this unique cirrus formation on the coast of Oman (Fig. 8) is virtually constant. The "grating constant" lies at approximately ten kilometers.

Elements arranged in rows can be found not only on a large scale in the macro-world, but also in the nano range of organic nature. Millions of years ago, nature was already using structures in the nano range to generate fascinating optical effects. The crystal-like structures of insects have already been investigated in great detail. Let us give two examples here: first, the colorful appearance of the ground beetle (Fig. 9, top picture, taken with an electron microscope) and second, the stridulatory organs of a velvet ant (Fig. 10, top picture, taken with an electron microscope). The grating constant of the stridulatory organ measures approximately 2.5 µm. In other words, there are even diffraction gratings that can crawl and fly.

Apart from the grating constant, a grating is defined, above all, by its groove profile.

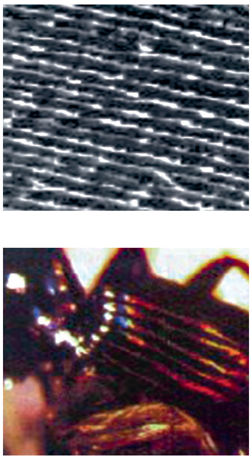

Fig. 9

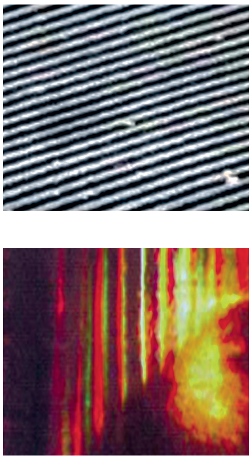

Fig. 10

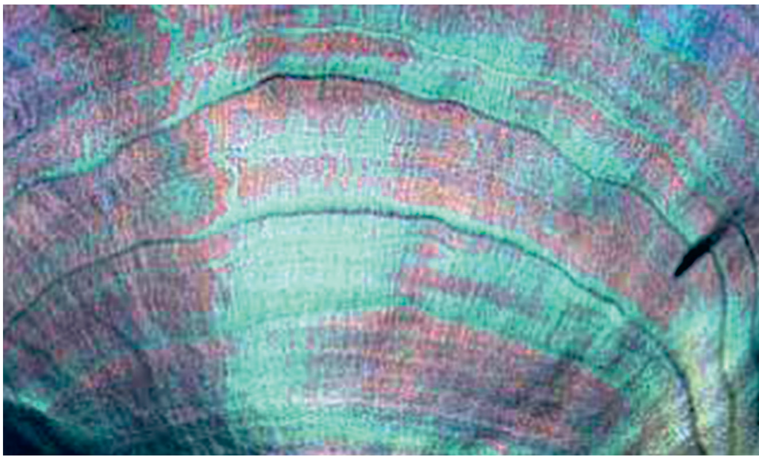

Fig. 11

Five different forms are currently used for diffraction gratings. If we add the semi-sinusoidal, Ronchi and Dammann profiles (special rectangular profiles), there are as many as eight. Suitable groove profiles can optimize the diffraction efficiency and definite diffraction orders can be ruled out. It appears that inorganic line arrangements occurring in nature consistently display sinusoidal groove profiles, while only lamellar profiles are encountered in biological systems.

The term 'diffraction efficiency' is used to describe an additional, function-defining property of gratings. The value expresses the extent to which energy can be obtained from diffracted light relative to the energy of the incident light. The diffraction efficiency depends on the angle of incidence of the incident light, the groove density, the profile shape and the regularity of the groove profile. This dependence can also be seen in the iridescence of a mother-of-pearl shell in nature (Fig. 11). The extent of iridescence can be correlated both with the groove density of the shell's diffraction grating and with the surface properties of the grooves themselves. A shell with 296 lines/mm displays strong iridescence, while one with 87 lines/mm only refracts light very faintly. The same phenomenon applies to pearls, but to a lesser extent.

In the bird world, humming birds and pheasants immediately attract attention with their iridescent plumage. Here, diffraction and interference go hand in hand. Biogenetically, such complex systems for color and pattern generation may be very old, as the fossil of a jewel beetle from the oil shale of the Messel pit demonstrates. It lived as many as 47 million years ago.

Fig. 12

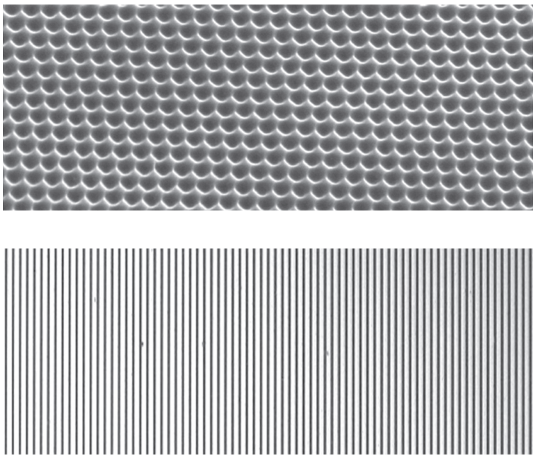

Fig. 13

People and lines

Regular lines obviously have major importance in our everyday lives. The property of directionality could be the reason why single lines and parallel line arrangements number among the fundamental cognitive structural units of humankind. The word comes from the Latin "linea" or "linum" and means "a straight line or thread". For Aristotle, symmetry and order were the extreme forms of beauty.

Therefore, the study of gratings, arranged either as natural or technical lines, could even convey a feeling of harmony to us. The Turkish poet Nazim Hikmet used the image of a vineyard (Fig. 12) to depict the beauty that he heard in the music of Bach.

Fall morning in the vineyard:
in row after row
the repetition of knotty vines,
of clusters on the vines,
of grapes in the clusters,
of light on the grapes,
of my heart in the light.
…
My rose, this is the miracle of repetition – to repeat without repeating.

Therefore, line arrangements stand for order and for beauty, i.e. they are used for both functional and esthetic purposes. For example, rasters like those seen in Fig. 13 (line grating of a scan at 3,000x magnification) are found as net-like systems of parallel lines in technical applications from the field of telecommunications and measuring technology as well as in art. Hatching and cross-hatching, for instance, have been used in printing technology in the western art world to generate dark-light effects or shadow since as far back as the 15th century.

In textiles, these effects are often created through the use of contrasting threads. The line pattern of a pinstripe suit is an excellent example of this. Rooted in the field of textiles (Latin "textura" cloth), the word "texture" is the overarching term used to describe the properties and appearance of surfaces. In the materials sciences it is used to describe the totality of crystallite orientations in polycrystalline solids.

Fig. 14

Fig. 15

The fine striations of natural quartz (Fig. 14) is an example of the texture of minerals and crystal appearance. It emerges during crystal growth when the conditions for crystallization change at constant time intervals.

From cloth, crystals and insect wings to metal or glass, there are evidently many gratings made of very different substrate materials. Therefore, a complete grating specification must always include an indication of the substrate material.

The start of this compendium described experiments from the 17th century for which natural grating structures were used. There is one modern-day grating that practically all of us have had in their hands at some time – the CD. Compact disks (Fig. 15) display long, linear grooves arranged concentrically on the disk. The indentations of this spiral-shaped track are 0.8 to 3.1 µm long and 0.5 µm wide. When you examine a CD from the outer to the inner edge, the sequence of equally spaced parallel lines is clearly visible. The line has an overall length of six kilometers and, in regular arrangement, forms the large number of lines of the CD diffraction grating. The grating constant would be 1.6 µm. If white light is incident on a CD, it is reflected, and the closely spaced tracks of the readable CD surface refract the light into a completely visible color spectrum.

BASIC PRINCIPLES OF OPTICAL GRATINGS

Optical structures have considerably influenced human evolution, even before we knew how they work. Not that we do know, we can achieve even more in the future.

Basic principles of optical gratings

Definition of parameters and symbols

Length of area with grooves, ruling width	L
Grating constant	0x0 (1)d
Distance of the groove centers	d = 1
Total number of grooves of a grating, groove number	N = L/g
Inclination angle-facet	θ
Angle of incidence and angle of diffraction	α and β
Angle of incidence and angle of diffraction (relative to grating facet)	α' and β'
Diffraction order	m
Light wavelength	λ

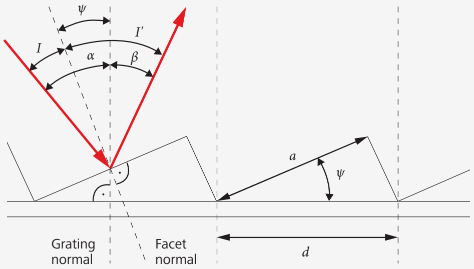

Fig. 16

Regular arrangements of elements that either absorb light or change the optical path length and hence the phase are referred to as diffraction gratings. This results in diffraction and interference, leading to wavelength-dependent deflection of light. This enables to examine the spectral composition of light. In the following a closer look on some properties of gratings and related principles of physics will be taken.

Grating equation

In the simplest case, a grating is comprised of a periodic arrangement of parallel grooves. If light falls on such a periodic arrangement, diffraction effectively transforms the grooves into a linear arrangement of point sources of reflected or transmitted light by diffraction. The special feature of diffraction gratings is that there are only discrete directions for a fixed wavelength for which the diffracted waves of all grooves are in phase and can thus interfere constructively. Therefore, for one wavelength there are only discrete directions with non - zero intensity. These are described as diffraction orders and enumerated.

Fig. 17 illustrates that for constructive interference $\sin(\beta) + \sin(\alpha) = m \cdot \lambda \cdot g$ must apply. This equation is referred to as the grating equation. It must be noted that the angle is usually measured counter-clockwise. Therefore, β would have a negative sign in the sketch shown.

Due to $|\sin(\beta) + \sin(\alpha)| \le 2$, only those orders for which $m \cdot \lambda \cdot g < 2$ is met can exist.

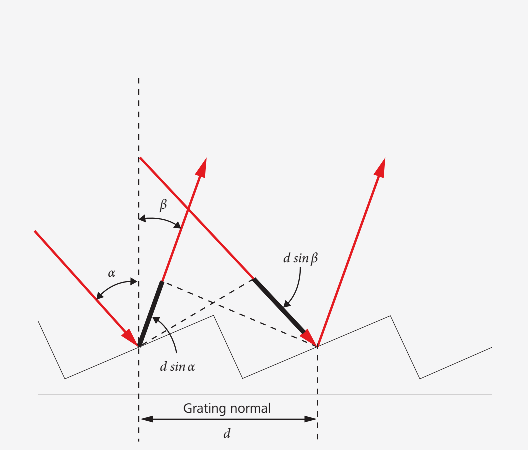

Fig. 17 Grating equation

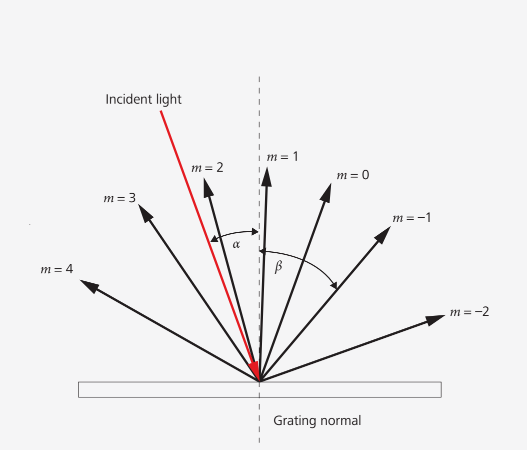

Fig. 18: Diffraction order

The zeroth order (m = 0) corresponds to reflection as it occurs in a mirror. The standard convention for numbering the zero and other orders is illustrated in Fig. 18.

Resolving power

The resolving power, $R = \lambda / \Delta\lambda$, of a grating is a dimensionless measure of its ability to measurably separate the maxima of two neighboring spectral lines with distance $\Delta\lambda$ from each other.

In accordance with DIN, the Rayleigh criterion is most commonly used for the measurability of a spectral distance $\Delta\lambda$: two neighboring spectral lines can be resolved as separate lines if a dip in intensity of at least 19 % can be measured between them.

With flat diffraction gratings, the theoretical resolving power can be determined with the Rayleigh criterion to $R = |m| \times N$. However, it must be noted that m and N can not be considered being indipendent.

A considerably clearer form can be determined via the grating equation:

$$\frac{Md}{\lambda}|\sin(\beta)+\sin(\alpha)| = \frac{L}{\lambda}|\sin(\beta)+\sin(\alpha)|$$

However, whether this theoretical value can be achieved actually depends on a large number of properties of the grating. For example, in addition to the optical quality of the grating surface and the precision of the groove position, the quality of the optics used in the system and the sizes of the entrance and exit slits play a key role.

Dispersion

For the dispersion of diffraction gratings, a distinction must be made between angular dispersion and linear dispersion. The angular dispersion D_β is simply the derivative of the diffraction angle as a function of the wavelength:

$$D_\beta = \frac{\partial\beta}{\partial\lambda} = \frac{m}{d\cos\beta}$$

The linear dispersion D_L depends on the effective focal length f' of the imaging optics of an instrument through $D_L = f' \cdot D_\beta$.

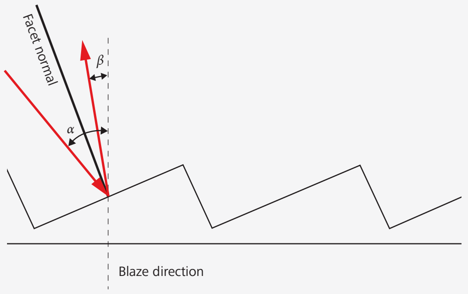

Fig. 19 Spectral range

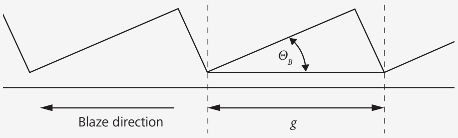

Fig. 20 Echelette grating; grating constant g=1/d; blaze angle Θ_B

Free spectral range

The wavelength range of a diffraction order, which is not overlaid with the spectrum of the next diffraction order is referred to as the free spectral range $\Delta\lambda$. This results in the mathematical definition $m(\lambda + \Delta\lambda) = (m + 1)\lambda$. The free spectral range is thus $\Delta\lambda = \lambda / m$.

Diffraction efficiency

One of the most discussed parameters for diffraction gratings is the diffraction efficiency **E**. The absolute diffraction effiency E_{abs} is defined as the ratio of the intensity of light I_m diffracted in the diffraction order m and the intensity I_{in} of the incident light with the same wavelength **λ:**

$$E_{abs} = \frac{I_m(\lambda)}{I_{Ein}(\lambda)}$$

In the same way, the more commonly used relative diffraction efficiency E_{rel} is defined as the intensity of a certain order relative to reflection of a mirror with identical coating:

$$E_{rel} = \frac{I_m(\lambda)}{I_{ref}(\lambda)}$$

The diffraction efficiency of a grating is primarily determined by the form of the groove, i.e. its profile. The maximum diffraction efficiency is usually achieved in autocollimation. Deviations from this configuration, also known as the Littrow configuration, normally lead to lower diffraction efficiency. However, this is usually only significant with very large angles. Theoretical predictions of diffraction efficiency are difficult but, if the profile is known, can be very accurately determined by using numerical methods. However, measurements of undiffracted and diffracted intensities are needed to determine the actual diffraction efficiency of a diffraction grating.

Groove profiles

The profile of the grooves of a grating can have different forms, depending on the requirements and production method. The most common profile forms are saw-tooth and sinusoidal profiles. Gratings with a saw-tooth profile are known as blaze or echelette gratings. Other grating profiles are occasionally used, e.g. laminar profiles.

Blaze or echelette gratings (saw-tooth profile)

A typical saw-tooth profile as can appear with gratings is illustrated in Fig. 20.

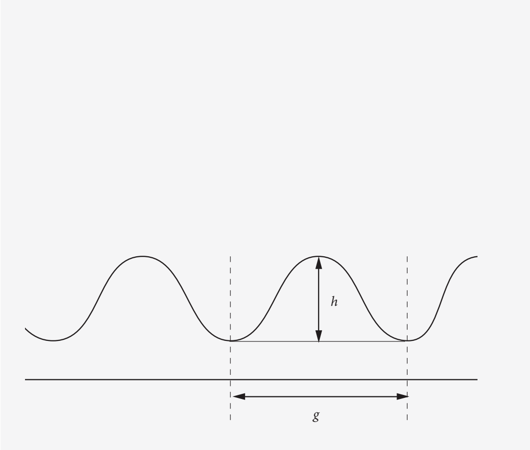

Fig. 21 Sinusoidal grating; grating constant $g=1/d$; profile depth h

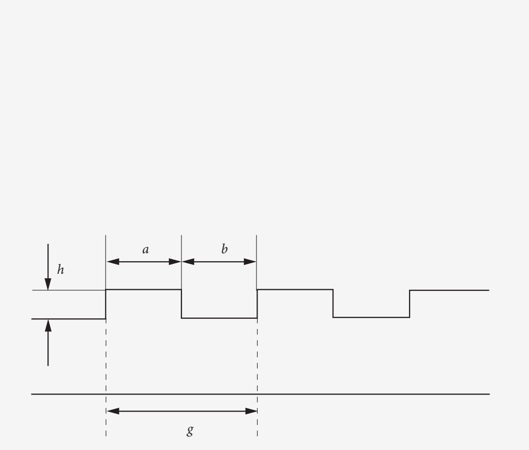

Fig. 22 Laminar grating; grating constant $g=1/d$; profile depth h; land-to-groove ratio $V = a/b$

A blaze grating is particularly effective if both the grating equation for the grating and the reflection condition for the groove facets are fulfilled. The wavelength at which the grating exhibits maximum diffraction efficiency is also known as the blaze wavelength λ_B. This blaze wavelength is determined through the inclination angle / theta of the groove facet and the groove density. In autocollimation the following applies: $\lambda_B = 2\ d\ \sin(\theta)$. Blaze gratings can be manufactured through both mechanical ruling and holographic exposure.

Sinusoidal gratings
Sinusoidal gratings feature a symmetrical, sinusoidal groove profile as illustrated in Fig. 21.

Due to the symmetry of the grooves, with orthogonal light incidence sinusoidal gratings diffract with the same intensity into the positive or negative diffraction orders in each case. Therefore, they are very good, for example, as symmetrical beam splitters. With a given groove density, the progression of diffraction efficiency is determined by the profile depth. This parameter can therefore be optimized to the spectral range in which the grating is intended to be used. Because the behavior of the diffraction efficiency strongly depends on polarization of the inciding light relative to the grating grooves, lower diffraction efficiencies are generally achieved for unpolarized light compared to blaze gratings. However, if polarized light is used, extremely high diffraction efficiencies can be achieved. As a result, and due to the broad spectrum of possible groove numbers, it is possible to develop sinusoidal gratings for a wide range of applications from VUV to IR.

Laminar gratings
Another possible grating profile related to sinusoidal gratings is the laminar profile. Such a profile is illustrated in Fig. 22.

Laminar gratings are defined not only by the groove spacing and profile depth, but also by the land-to-groove ratio. One difference to sinusoidal and blaze gratings is that some diffraction orders can be suppressed. This can be achieved by optimizing the land-to-groove ratio and can lead to very high diffraction efficiencies. In particular, if the step height is $h = \lambda/4$, the zero order disappears when the land and groove width are identical. The result is maximum intensity in the first order for the blaze

Carl Zeiss is able to manufacture gratings with extremely low stray light.

wavelength $\lambda = 4h$. Additionally, a laminar grating usually causes considerably less stray light than sinusoidal or echelette gratings. Both make laminar gratings particularly suitable for wavelengths in the UV range and below.

Stray light

In the use of gratings, different types of light can appear where it is not wanted. This light is referred to as stray light. There are a number of possible sources for unwanted light, e.g. diffuse scattered light from the grating, grating ghosts, reflections occurring during an application or unwanted diffraction orders.

Higher orders

Higher orders of diffraction are particularly problematic if gratings are to be used for very large wavelength ranges which are considerably larger than the free spectral range.
For example, filters have almost always to be used with polychromators and monochromators in order to keep the higher diffraction orders of shorter wavelengths at the sensor or exit slit at bay. Additionally, the zero order usually has to be taken into account in the design, otherwise it can lead to pronounced stray light in a device.

Grating ghosts

In mechanically ruled gratings periodic ruling errors occur which cannot be technologically avoided, but only minimized. These errors work like an additional grating and lead to unwanted overlay with additional spectra of very low intensity. These lines are described as ghosts.

On the one hand, such errors of the groove position occur with very long periods. This leads to ghosts near the actual spectral lines and can also occasionally cover them. These ghosts are also referred to as Rowland ghosts.

On the other hand, groove position errors also occur with very short periods of, for example, only two grooves. This leads to lines that are distributed with large distances in the spectrum and are described as Lyman ghosts. Because the interference of two laser beams determines the groove position for holographically produced gratings, no such ghosts occur due to the way in which they are produced.

Scattered light

All diffraction gratings exhibit diffuse scattered light between the orders of diffraction. This scattered

light can occur through random groove displacement of mechanically ruled gratings, through microroughness of the reflective coating and through possible false light during holographic exposure. At ZEISS, diffuse scattered light is kept extremely low by creating suitable conditions during manufacture of the master and through the use of optimized processes. The outstanding properties of the master grating can only be transferred to replicas through the extremely high quality of the replicating process. Therefore, ZEISS is able to manufacture gratings with extremely low stray light.

Transport, storage and cleaning

Diffraction gratings from ZEISS are delivered in an appropriate packaging which is also suitable for shipment to tropical countries. The gratings can be stored in normal indoor conditions. However, the gratings should be protected against dust and other types of contamination.

Unsuitable conditions include high humidity, extreme temperature fluctuations and contact with oil and solvent vapors.
In tropical countries and regions with high humidity, in particular, storage in air locks is recommended to minimize the risk of fungal infestation.

In general, the grating surface must not be subjected to mechanical stress, otherwise the grating grooves can be significantly deformed as a result of the low hardness of the replication resin compared to glass or metal. Furthermore, breathing on the grating surface or "talking over the grating surface" must be avoided as it can lead to significant contamination. Liquid cleaning agents are not recommended under any circumstances. Blowing with dry air or dry nitrogen with maximum pressure of 3.000 hPa, or with a rubber ball are the only recommended cleaning methods. Occasionally, rinsing a grating under running ultrapure water can lead to good results.

GRATING PRODUCTION AND GRATING INSPECTION

When it comes to the production of gratings of the highest quality, one name springs to mind immediately: ZEISS.

Grating manufacture

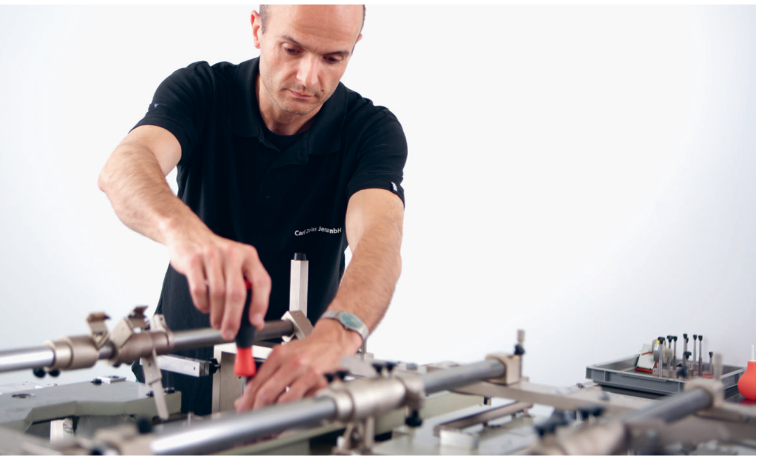

Fig. 23 Production of mechanically ruled gratings

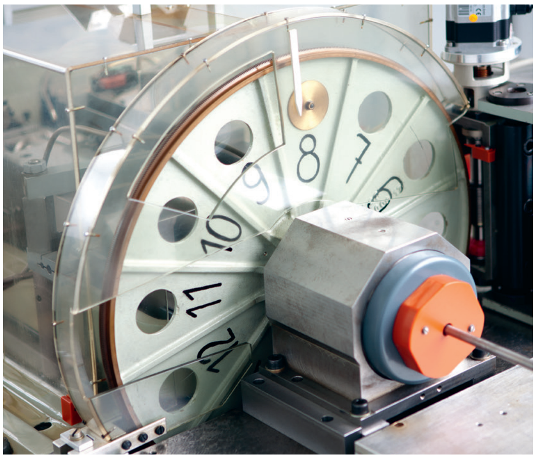

Fig. 24 Ruling engine

At ZEISS gratings are produced either by mechanical ruling or by holographic exposure.

Mechanical ruling

ZEISS can produce mechanically ruled gratings for the spectral range between 150 nm and 40 µm with groove densities of 3 mm^{-1} to 2,600 mm^{-1}. The groove length of the existing engines is limited to 110 mm, and the ruling width to 120 mm.

Method

For the mechanical ruling of diffraction gratings two Rowland-type ruling engines are available. They are contained in climate-controlled cabins in order to minimize external influences during the ruling process.

In the ruling process a diamond is used to burnish parallel, equidistant grooves (lines) to a plane substrate. The sequence of grooves is achieved by first using the diamond to make a groove and then continuing to move the substrate by one grating constant perpendicularly to the groove direction. Whether a cutting or non-cutting process is used depends on the groove density and the material in which the ruling is to be performed. The preferred substrates are glass types that have been coated with a metallic reflective layer, e.g. aluminum, gold or copper. However, mono- and polycrystalline layers have also been ruled for several years now. This allows the production of crystalline grating prisms (grisms).

As the intensity of the light diffracted at the grating is dependent on the groove form, a diamond with a suitable shape must be selected for the ruling. This diamond must be chosen considering groove density, blaze angle, ruling material and also whether a cutting or non-cutting technique is more suitable to achieve smooth groove facet and hence a low level of stray light.

The machine setup and the subsequent ruling of a master can take more than one week. Therefore, it is the possibility of producing high-quality grating replicas that makes this process economically interesting in the first place.

Benefits

Mechanically ruled gratings are particularly suitable for systems that require high resolution.

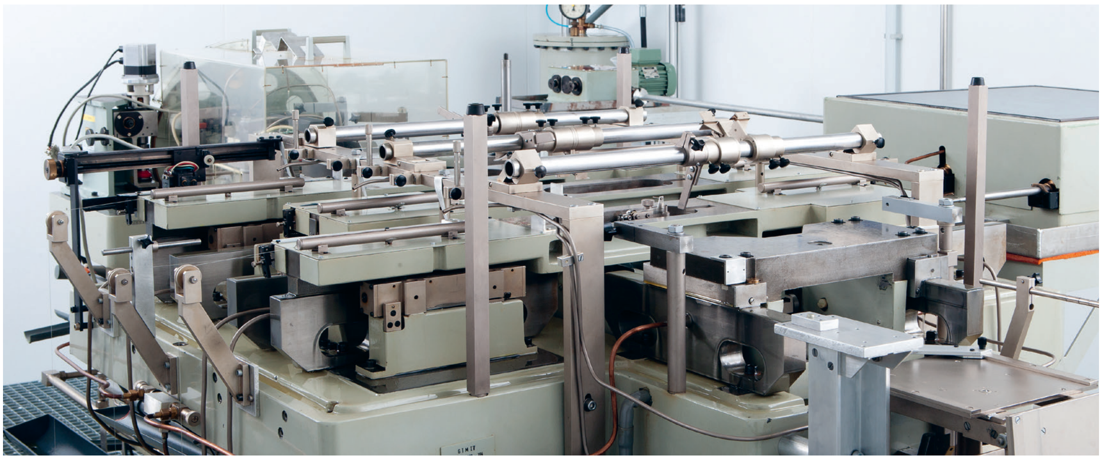

Fig. 25 Ruling engine

The outstanding features of the mechanically ruled ZEISS gratings include:

- Uniform line sequence: This leads to low stray light. This means spectrometers can be built that offer very high detection sensitivity for low-intensity signals and high measuring accuracy in the visual and infrared spectral ranges.
- Few grating ghosts: Grating ghosts are the result of periodic substructures in the grating. They can be caused by irregular operation of the ruling engine.
- Low stray light: Random groove displacement or local deviations from the ideal profile shape, i.e. through roughness, cause diffuse stray light. The suitable selection of the ruling layer, favorable production conditions, precise adjustment of the ruling process, optimum selection of the ruling diamond and the high quality of the replication process keep diffuse stray light extremely low.
- High resolving power: The theoretically attainable resolving power of a grating is defined by the product of the total number of grooves with the diffraction order. It is approximately attained if the deviations of the wavefront diffracted by the grating are small compared to the wavelength used. High optical flatness of the grating surface and adequate freedom from systematic, periodic and random errors of the grating constant are required for this purpose.

Holographic exposure

ZEISS can produce plane and concave gratings for the spectral range between about 9 nm and 4 µm with groove densities of 40 mm^{-1} to 6,400 mm^{-1} .

Method

The holographic or interference lithographic process is used to create gratings by relief-type recording of a narrow laser interference field in a photoresist layer. The idea of using light itself for the manufacture of diffraction gratings is not new. Michelson published proposals on this process as early as 1915. However, it has only been possible to manufacture high-grade spectroscopic gratings since photoresist coatings capable of high resolutions and lasers with short wave radiation have become available. Using these as a starting point, ZEISS has developed new manufacturing technologies and is now making holographic gratings for a wide range of applications.

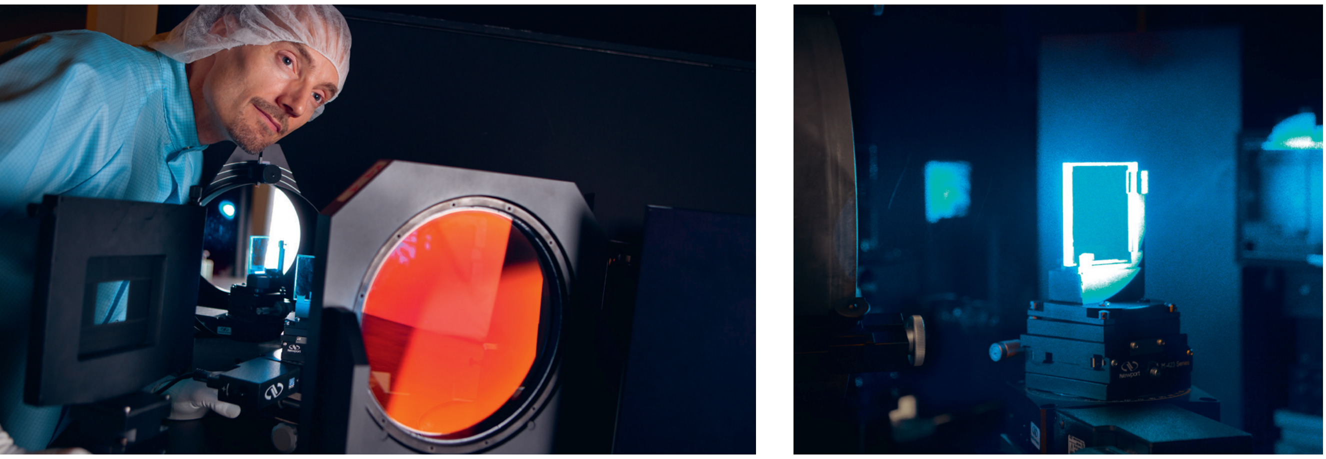

Fig. 26 Production of holographically corrected concave gratings

In holographic grating exposure the grating substrates are initially coated with a photoresist with thicknesses between 0.1 und 3 µm by means of spin coating. This photoresist is then exposed to the interference field of two laser light beams. For this purpose, extremely uniform interference fields are used in order to generate planarity of $< \lambda/4$. Interferometric inspections additionally ensure that the wavefront aberration is always $< \lambda/4$. After the photoresist has been developed, a surface relief is created by washing the exposed parts (positive photoresist). This surface relief is finally provided with a reflective coating (e.g. aluminum or gold) and occasionally also with a protective coating .

The use of non-linearities of the photoresist's characteristic line and processing by pre-exposure, standing waves, etc. allow a broad range of groove profiles. These include:

- sinusoidal
- semi-sinusoidal
- laminar/binary
- blaze/echelette

The interfering waves can be created by wave-front or amplitude splitting of coherent laser beams. The axes of these interfering laser beams are directed at the vertex or center of the grating substrate. Depending on the desired grating properties, the interference pattern can be generated with two collimated beams, two point sources generated with objective lenses or one collimated beam and one point source. The light sources used are generally Ar or HeCd lasers in single-mode operation.

Extremely stringent demands are made on the mechanical stability of such an interference setup. At ZEISS the interference image is additionally stabilized via interferometric checks and piezo-ceramic control during the exposure.

Concave gratings

Concave diffraction gratings combine dispersive and imaging properties in a single element, making them ideal for modern spectroscopic systems. The basic form of all imaging gratings is the Rowland circle grating. At ZEISS all concave gratings are produced holographically. The radii can be selected over a large range, allowing aperture ratios of up to 1:1.

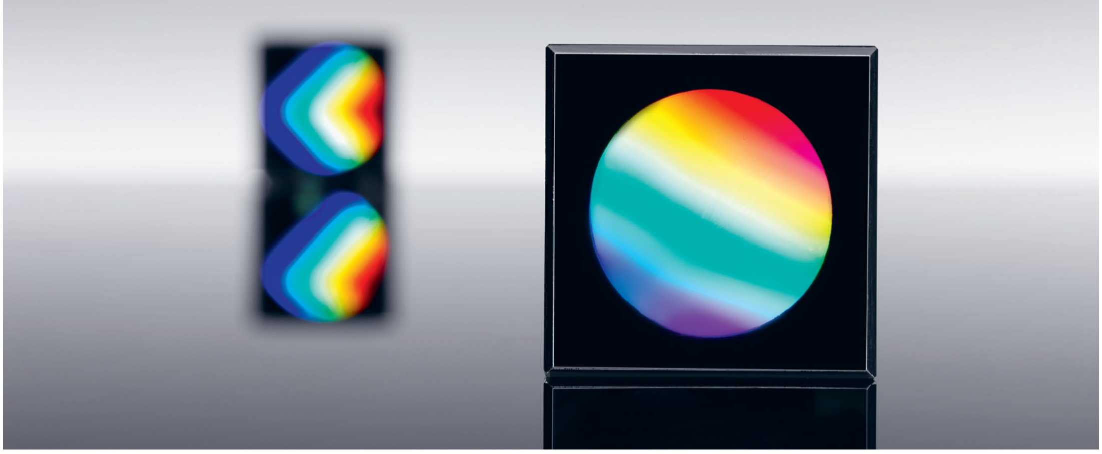

Fig. 27 Concave gratings

The use of concave gratings allows systems with a relatively small number of components. This not only reduces stray light, but also increases light intensity.

Holographically corrected concave gratings

Holographic correction during production of concave gratings can simultaniously optimize the focal plane and minimize aberrations such as astigmatism, spherical aberration and coma over a wide spectral range.

Unlike Rowland circle gratings, these aberration-corrected gratings feature grooves with variable spacing and variable curvatures. This holographic design allows optimum adaptation of a grating's imaging properties to the specific requirements of the spectral device 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 spectrometers and miniaturized spectrometer modules at a viable cost. With holographic gratings featuring corrective properties – unlike classical concave gratings – it is possible to vary the position of the focal lines over a wide range. This results in new, simpler ways of designing dispersive optical systems:

- Monochromator arrangements consisting only of fixed entrance and exit slits and a grating rotating around its axis
- Spectrometers of the polychromator type without movable parts, featuring a fixed grating and a flat diode array covering all wavelengths of interest
- Spectrographs with a fixed entrance slit, fixed grating and, for example, 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, gratings with corrective properties can be beneficial

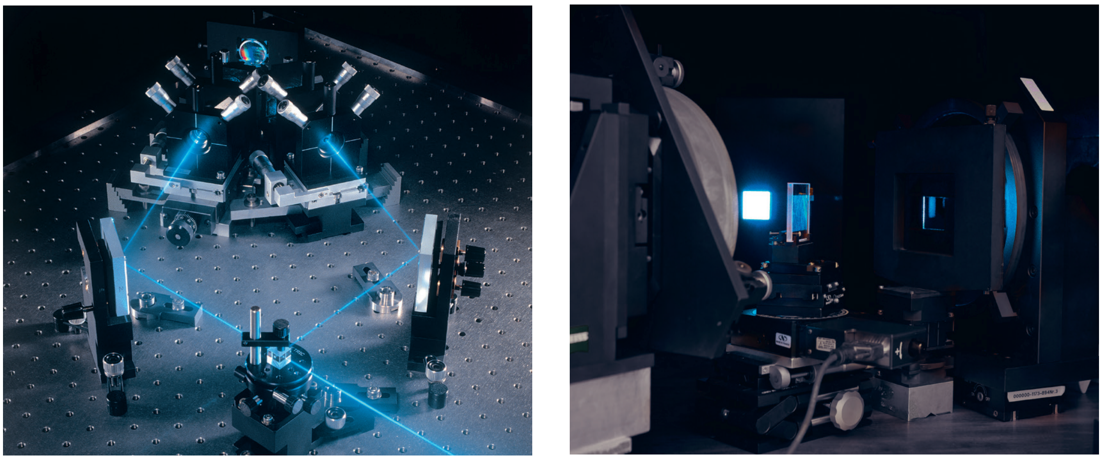

Fig. 28 Production of holographically corrected concave gratings

Production of holographically corrected concave gratings

Concave gratings with corrective properties are produced in an interferometer setup adapted to the potential use of the grating. As with holograms, this results in aberration-free imaging for the production wavelength. 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 high-performance dispersive systems. Unlike the conventional exposure procedure using plane waves, two spherical waves, partly with deliberate aspheric distortion, are made to interfere in the photoresist layer of the grating substrate in order to generate holographically corrected gratings. The following configurations are mainly used for this purpose:

Symmetrical profiles (Fig. 29)

This principle is used 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.

Blaze profiles (Fig. 30)

This principle is used to produce gratings with a saw-tooth groove profile (echelette and blaze gratings). They display particularly high efficiency in a specific wavelength range. The two interfering waves incide on the photoresist from two opposite directions, resulting in a steep inclination of the nodal and anti-nodal planes of the interference field. During the development process, the removal of the material continues along the anti-nodal planes, with the nodal planes acting as barriers. After a specific development time, the groove profile assumes the desired saw-tooth shape. To prevent grating ghosts and stray light, an antireflective coating is vacuum-deposited on the back of the grating substrate, through which the convergent wave is incident during exposure.

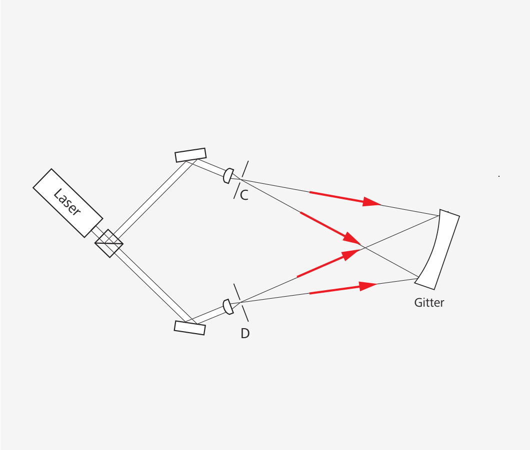

Fig. 29 Symmetrical profile

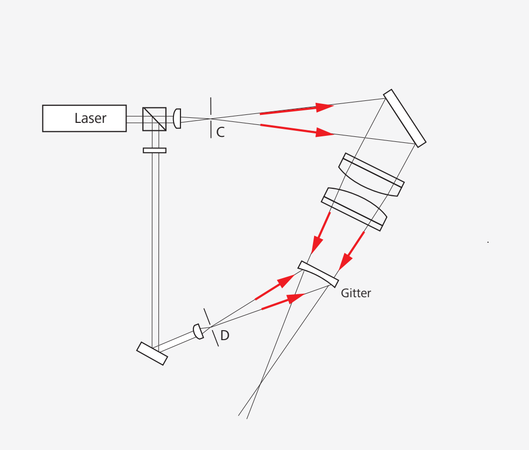

Fig. 30 Blaze profile

Benefits
Holographic gratings display a lower level of stray light by typically at least one order of magnitude and are totally free from ruling errors (grating ghosts) compared to mechanically ruled gratings. Another benefit offered by these gratings is that special optical imaging properties can be realized which cannot be achieved using mechanical means, e.g. the correction of aberrations in concave gratings. Holographic gratings are easy to produce in cases where mechanical ruling requires more outlay, e.g. if the ruled areas are large and the groove density is high.

ZEISS has optimized the groove profile of holographic gratings so that even the zero diffraction order is largely suppressed. The exceptionally high efficiency of such gratings equals that of ruled echelette gratings, or indeed clearly surpasses it when polarized light is used.

As extreme freedom from stray light is not always required and good replication technology makes the type of production less important, mechanically ruled and interference-based gratings are used side by side. The production of long, straight blaze flanks for echelette gratings with e.g. 60 lines per mm (L/mm) is extremely difficult on a purely interferential basis and should be restricted to mechanical ruling engines. A wide selection of profiles that have been produced with ruling frequencies above 200 L/mm are now commercially available.

Ion beam etching

If a solid surface is bombarded with ions, individual atoms are dislodged. Argon ions with an energy of 1 keV are frequently used for this purpose. Here, the implantation rate is of negligible significance. One major benefit of this method is that, unlike laser machining or mechanical polishing, no mechanical stress is induced in the material. In addition, the micro-roughness of material machined in this way is not generally influenced.

In ion beam etching of diffraction gratings, oxygen ions are normally used to transfer the groove profile from the photoresist to the substrate material. On the one hand, this means that the master gratings display increased thermal and mechanical stability. On the other hand, in addition to transfer with contour accuracy, it provides the possibility of targeted profile manipulation during transfer. Unetched holographic blazed master gratings generally display

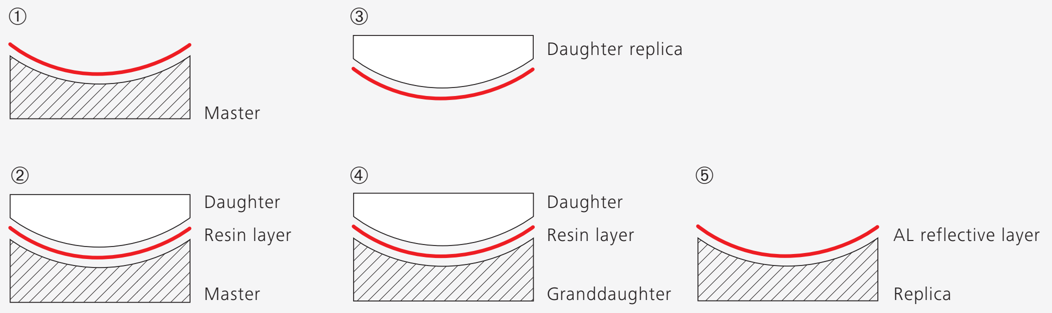

Fig. 31 Replication method

a blaze wavelength of around 230 nm. The targeted change of the groove profile permitted by ion beam etching allows shifting of this blaze wavelength to shorter or longer wavelengths. This enables ZEISS to produce aberration-corrected blaze gratings for spectral ranges from soft X-ray to the infrared range.

Laminar gratings with rectangular groove profiles display extremely low stray light after ion beam etching. The low micro-roughness of the substrate surface during the manufacturing process on the groove surfaces remains unaffected.

Replication

Almost all plane and concave gratings are higher-generation replicas whose properties, however, correspond to the masters to the greatest possible extent.

Method

Replication technology allows cost-effective, high-volume production of high-quality gratings. With the replication method developed by ZEISS, it is possible to use any grating master manufactured by one of the methods previously mentioned to produce numerous replicas whose properties and quality equal those of the master.

The following steps were performed in the replication process:

- The starting point is a master grating, e.g. a holographic, concave grating with a saw-tooth groove profile.
- Through the application of a resin layer and of a convex substrate, the structure is replicated onto a submaster or 'daughter'.
- The daughter with the negative structure is then available as a replicating tool.
- The 'granddaughter' grating is produced through repeated replication into a resin layer of a concave substrate.
- After the granddaughter has received a reflective coating (e.g. aluminum), a virtually identical replica is then available.

Grating inspection

Fig. 32 Concave gratings are provided with a reflective layer that matches the spectral range used.

In order to guarantee high quality on an ongoing basis, not only the final inspection of the grating, but also inspection during manufacture is of decisive importance. Usually, there are many individual properties which are important for the functionality of a grating. Therefore, the following indicators are already checked on the grating substrates used for the replication process:

- Materials
- Dimensions
- Radius of curvature
- Surface quality/cleanliness

For the complete grating, a number of other parameters can be specified. The most important of these are explained in the following. For critical dimensions, a special inspection procedure can be agreed upon if necessary.

Dimension of grating surface

The length and width or diameter of the diffractive surface and its position on the grating substrate can be tested on the basis of defined specifications.

Groove density and groove spacing

The groove spacing can only be directly measured with high accuracy on very coarse grids. Therefore, the diffraction angles of a laser beam are normally measured, and these are then used to determine the groove density. This enables accuracies of up to 0.02 %. Due to the small beam diameter of the lasers used, both flat and curved gratings can be inspected.

Groove profile

The quality of the groove profile is generally evaluated by measuring the optical properties of the grating. Direct measurement of the groove profile, e.g. through atomic force microscopy, contact or optical profilometers, is also possible, of course, and can be performed at the customer's request.

Reflective coating

The extent of the diffraction efficiency of reflection gratings is decisively determined by the reflectivity of the grating surface. Therefore, gratings are provided with a reflective layer that matches the spectral range used. Typically for the UV, VIS and NIR ranges, this is aluminum, and gold for the IR range. In general, no inspection of the reflective

ZEISS has optimized the groove profile of holographic gratings so that even the zero diffraction order is largely suppressed.

coating exceeding the grating efficiency measurement is necessary, but can be performed at the customer's request. In particular if protective coatings like SiO_2 or MgF_2 are necessary, such an inspection may occasionally be meaningful. However, this is required in very rare cases only, e.g. for very high laser powers. To be on the safe side, witness samples are also coated in each coating process so that the quality can also be tested on them if necessary.

Diffraction efficiency

Usually, the efficiency is specified under the Littrow condition or in autocollimination. As no measurement can be conducted in this configuration, the measurement is generally performed with a finite deviation angle. The respective grating determines at what angle the measurement is performed. Needless to say, non-standard measuring conditions are also feasible. The diffraction efficiency can then be determined through multiplication of the relative diffraction efficiency by the reflectance of the reflective layer.

Cleanliness and quality of the grating surface

The occurrence of cosmetic defects in the grating structure can never be totally avoided in grating replication. However, their influence on the functionality of the grating is, at the very most, as big as their proportion of the overall diffractive surface. Even if their influence on the grating performance is generally negligible, all gratings are visually inspected for cosmetic defects and cleanliness by our quality assurance team using comparative samples and are only delivered if they pass these tests.

Stray light

To specify diffuse stray light of gratings, the monochromatic stray light coefficient and the integral stray light are mainly used. For monochromatic stray light, a setup similar to that for the measurement of diffraction efficiency is used. Here, a grating is illuminated monochromatically and the light intensity between the diffraction orders is measured. This is then normalized to the intensity of the used order (usually the first order) and the solid angle at which the grating is seen from the exit slit. To determine the integral stray light, the grating is illuminated with a continuous light source and the

diffracted spectrum is measured with and without a notch filter. This notch filter absorbs a defined part of the spectrum, which is why it should no longer be possible to measure any intensity in this spectral range with an ideal grating. Then the measure for stray light is normally the minimum intensity in a spectral range selected to match the filter, specified in absorption units relative to the measurement without a filter. As the environment of the setup (e.g. a housing), the filters and the light source used play an extremely important role here, they must also always be defined in the specification of integral stray light.

Imaging properties

The imaging properties of concave gratings show up in the location and form of the monochromatic images of the entrance slit with a fixed distance and angle of the entrance slit relative to the grating. Due to astigmatic aberrations, there is a tangential and a sagittal focus or image distance for the slit images. To obtain optimal resolution, the slit or detector should be positioned in the tangential focus. Spherical aberration and coma will additionally occur. To check whether these aberrations are found within specified limits, the grating must be brought into a geometric configuration that corresponds to that of the instrument in which the grating will later be used.

Spectral resolving power and wavefront

The spectral resolving power of an imaging grating is normally specified by a spectral bandwidth such as, for example, full width at half or tenth maximum. This depends not only on the imaging properties but also on any position and form errors of the grooves and the additionally used optics. For an inspection, therefore, optics and configurations identical to the application case have to be applied. By using interferometric measurements, the resolving power can be tested in an indirect manner for plane gratings. Here, wavefront aberrations are a measure of ruling or planarity errors. The test can be performed in the zero order (flatness testing), in blaze (application setup) and in a higher negative order. The latter is of interest for mechanically ruled gratings as it allows better detection of any ruling errors that may have occurred.

Even if they display different properties, optical gratings from ZEISS have one thing in common: premium quality.

Grating types

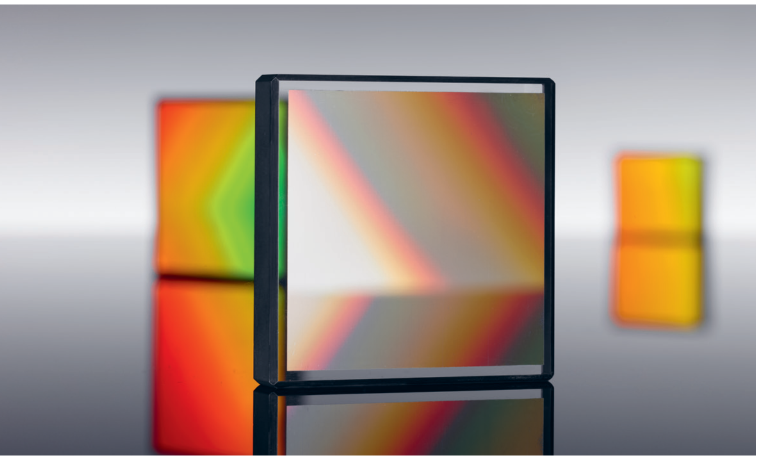

Fig. 33 Plane gratings

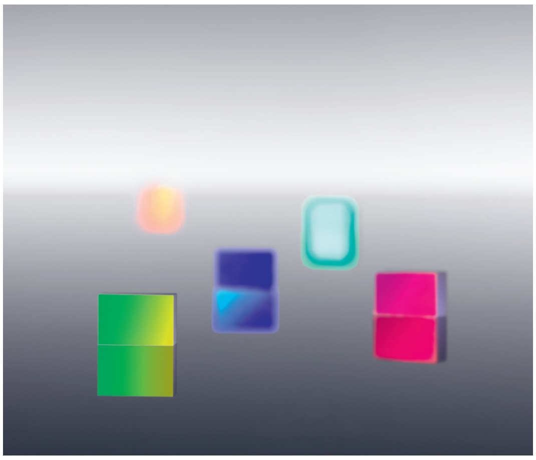

Fig. 34 Laser gratings

Plane gratings

Plane gratings is the term used to describe flat diffraction gratings. They have the broadest range of applications of all diffraction gratings:

- monochromators
- polychromators
- laser technology
- beam splitting
- aerospace engineering
- reflection standards

Plane gratings from ZEISS are optimized for spectral ranges between 100 nm and 50 µm. The gratings are mechanically ruled or holographically recorded depending on what method promises the better result. The possible grating profiles are:

- echelette or blaze
- sinusoidal
- laminar

Laser gratings

In laser technology both plane and imaging gratings are used inside and outside the resonator. They are generally used for:

- wavelength selection
- beam splitting
- beam shaping
- polarization

Laser gratings from ZEISS are optimized for spectral ranges between 200 nm and 12 µm. The parameters determining functionality are:

- line density
- groove profile
- the resulting diffraction efficiency
- wavefront accuracy
- resolving power
- imaging properties
- substrate material
- the associated radiation resistance

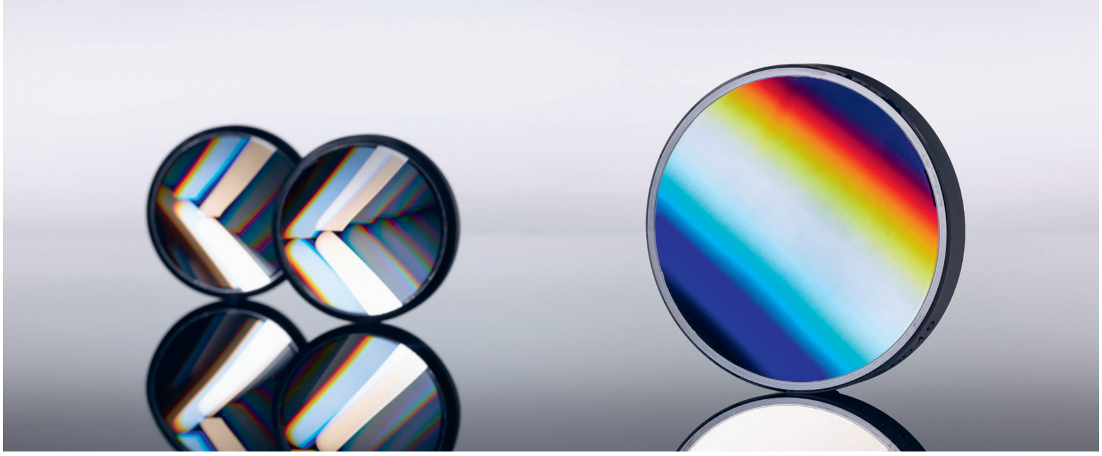

Fig. 35 Concave gratings

Regarding diffraction efficiency, here the absolute value is more relevant than in most other applications. To achieve maximum efficiencies, deliberate use is made of the polarization dependence. However, maximum diffraction efficiency is not always needed for laser applications. Medium to low diffraction efficiency may occasionally be sufficient, or indeed desired.

Concave gratings

Concave diffraction gratings combine dispersive and imaging properties, making them particulary suitable for constructing compact, stable spectroscopic systems. The concave gratings offered by ZEISS are holographically produced gratings as they are found on a spherically curved surface. In case of customized gratings the radius of curvature of the sphere can be selected rather free, allowing aperture ratios of up to 1:1. The benefit of concave gratings is the possibility of designing a system with few components, therefore reducing stray light and increasing light intensity. ZEISS concave gratings are normally divided up into three groups which are briefly described in the following:

Rowland circle gratings

Rowland circle gratings represent the basic form of imaging concave gratings. In the Rowland circle configuration the entrance slit, grating and detector are located on a circle, the diameter of which equals the radius of the grating substrate.
This configuration ensures that the imaging of the entrance slit is free from defocusing as well as primary coma and displays only minimal spherical aberrations. Although pronounced astigmatism is

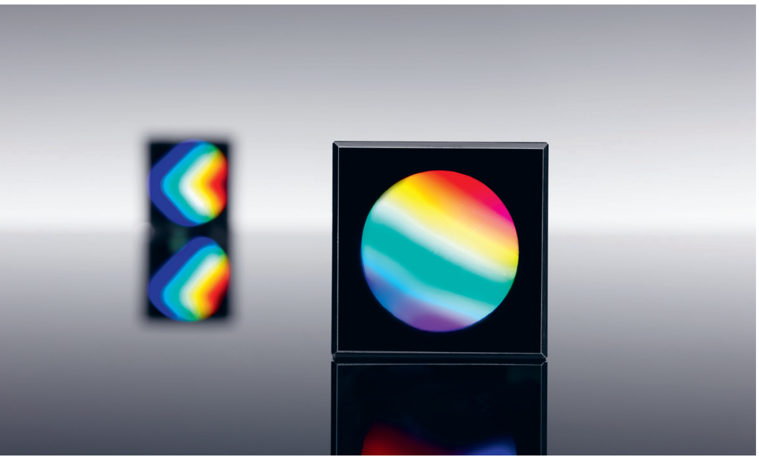

Fig. 36 Concave gratings

present, the resulting elongation of the slit images does not significantly reduce the resolving power. The grating structure of a Rowland circle grating, projected onto the plane surface tangent to the vertex, consists of equidistant straight grooves.

Aberration-corrected concave gratings

While Rowland circle gratings can be produced by both mechanical ruling and holographic exposure, aberration-corrected concave gratings are always holographically generated gratings. Unlike Rowland circle gratings, the grooves of such aberration-corrected gratings have variable distances and curvatures. This allows optimization of the focal surface and simultaneous minimization of aberrations like astigmatism, spherical aberration or coma for a broad spectral range.
This allows optimisation of imaging properties according to the requirements, as well as changing the position of the focal line within a wide regime. This makes it possible to implement robust, compact and high-resolution spectral systems containing a small number of components.

Depending on the type of optimization, a distinction is generally made between monochromator and polychromator gratings. Monochromator gratings are optimized for a setup with fixed entrance and exit slits and a grating rotatable around a fixed axis. Unlike Rowland circle gratings, the focus of a monochromator grating does not move out of the plane of the exit slit during the rotation, which, together with the reduced aberrations, leads to greatly improved resolution.

Polychromator gratings are optimized for setups with fixed arrangements of entrance slit, grating and plane sensor. The holographic production of such gratings makes it possible to achieve an approximately flat focal surface in addition to aberration reduction. This allows to image the spectrum that is dispersed by the grating with high resolution on a flat receiver such as a one- or two-dimensional CCD sensor.

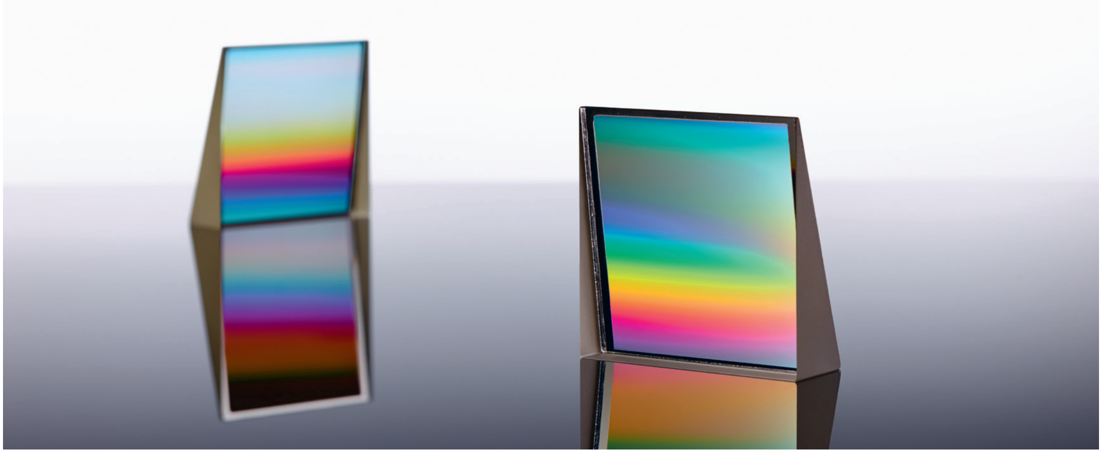

Fig. 37 Grating prisms (GRISMs)

Grating prisms (GRISMs)

A grating prism is a prism that has a transmission grating on one of its plane surfaces. In rare cases a grating prism can also have two gratings or curved surfaces. The portmanteau word "grism" (GRating+prISM) is often used.

Most grisms are used for slitless straight view spectroscopy, e.g. in astronomy. By combining grating and prism in a single component, the grating constant and apex angle of the grism can be varied to choose an undeviated wavelength, the mean wavelength or straight view wavelength with respect to the incident light. By swinging a grism into the collimated beam path of a camera, spectroscopy can be performed around this mean wavelength; the camera becomes a spectrograph.

Grisms are suited for applications with wavelength roughly between 115 nm and 30 µm. The transmission grating is usually located on the hypotenuse surface of the prism. Depending on the prism material, the grating is either replicated onto the prism or ruled directly into the prism material. The groove profile is usually (exclusively in the case of direct ruling) saw tooth-shaped, and the blaze angle is normally identical to the apex angle of the prism, with the result that the straight light path displays high diffraction efficiency.

APPLICATIONS OF OPTICAL GRATINGS

Optical gratings can be precisely tailored to the intended application. This is why we at ZEISS see close partnership with our customers as an absolute must for the development of grating solutions.

Applications of optical gratings

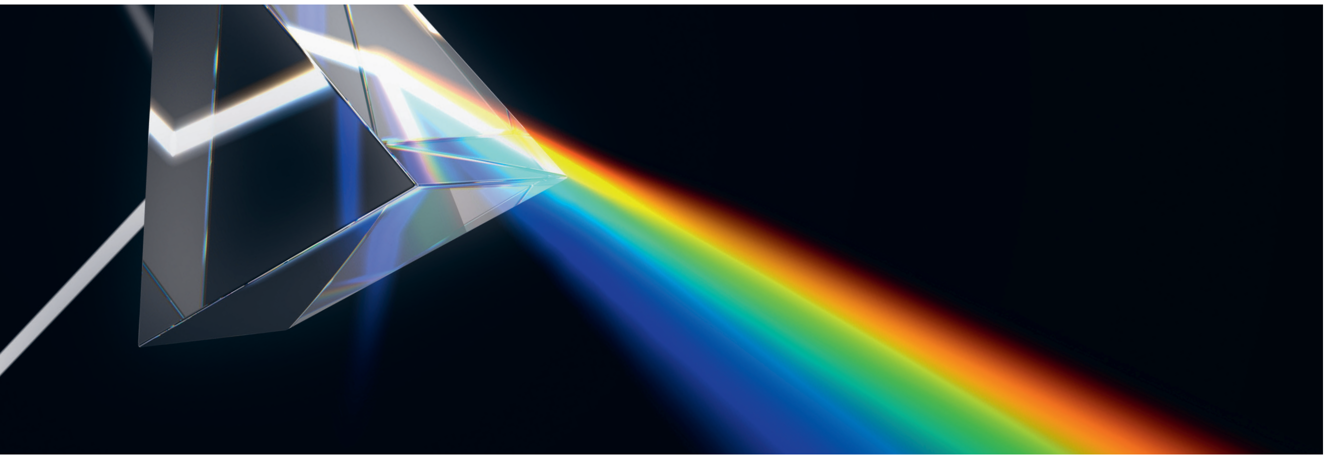

Fig. 38 Light splitting as the basis of spectroscopy

Spectroscopic devices

Spectroscopy, in general, is the term used to describe the measurement of an energy spectrum. To do this, radiation is analyzed by its energy. Instead of the energy E, usually the wavelength λ, wave number $\tilde{\nu}$ or frequency ν are given. These parameters are related via $E = h \cdot \nu = h \cdot \frac{c}{\lambda} = h \cdot c \cdot \tilde{\nu}$. h describes Planck's constant and c the speed of light in a vacuum.

In most applications, spectroscopy is used to examine the interaction of electromagnetic radiation with matter. It determines at what wavelengths electromagnetic radiation can be absorbed, reflected or emitted by a specimen. To analyze the electromagnetic radiation over a wide spectral range from UV to NIR, gratings are commonly used.

In spectroscopy, a distinction can generally be made between monochromators and polychromators. While single wavelengths are probed with a monochromator, a polychromator tries to record the entire spectrum at one go.

Principle of the monochromator

A monochromator (Greek "mono" = one + "chroma" = color) isolates a specific wavelength from incident electromagnetic radiation. This incident radiation can be comprised of a wide range of wavelengths, of which those that are unwanted are absorbed or deflected.

With a monochromator, light is seamlessly expanded depending on its wavelength. This occurs through a dispersive element which is usually either refractive (e.g. a prism) or diffractive (e.g. a diffraction grating). Through a split diaphragm, a minimal wavelength range, i.e. a color, of light is selected with the desired wavelength. This slit can be seen as the secondary light source. The unwanted wavelengths are absorbed by the slit.

The quality of the wavelength selection, i.e. spectral width and intensity of the radiation exiting the monochromator, depends on several parameters. With high dispersion, a lower spectral width with lower intensity is possible. Large slit widths enable high intensity, but also lead to a high spectral width. Furthermore, the spectral range and

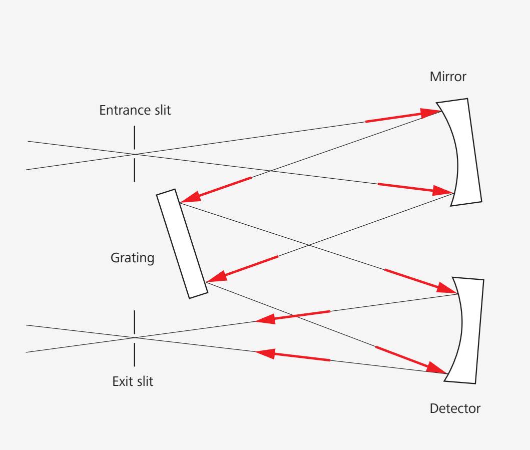

Fig. 39 Czerny-Turner configuration

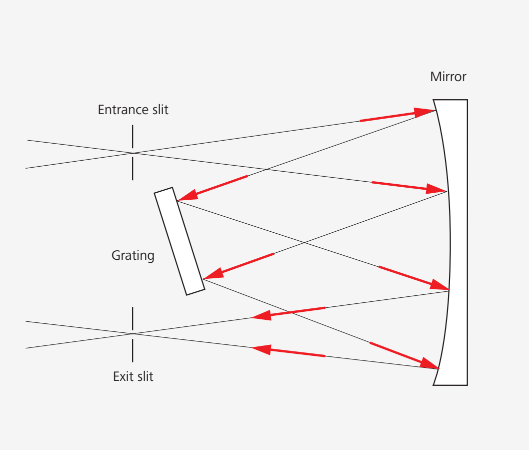

Fig. 40 Ebert-Fastie configuration

intensity can be improved through the optimization of the image of the entrance slit on the exit slit.

An imaging monochromator grating enables good optical imaging of the entrance slit on the exit slit. The quality of this image should change as little as possible when the grating rotates and the exit wavelength is thus modified.

Principle of the polychromator

A polychromator (Greek "poly" = many + "chromos" = color) enables the determination of the entire wavelength spectrum. In principle, imagine a monochromator in which a line or surface detector is located in place of the exit slit. This enables the simultaneous analysis of the entire spectrum; this is very beneficial if spectra are to be obtained at high speed. Unlike a monochromator, an imaging grating on a polychromator must image the entrance slit, spectrally separated, as well as possible on one line. Additionally, mechanically moving parts are not required on a polychromator, which simplifies production, enables long-term stability and increases mechanical durability.

Typical configurations

The simplest configuration for mono and polychromators with a plane grating is comprised of an entrance slit, a spherical concave mirror that converts light into a parallel light bundle, the plane grating which diffracts light, and a second spherical concave mirror that focuses the light on the exit slit or the linear detector. This W-shaped configuration is also known as the Czerny-Turner configuration. A widely used variation of the Czerny-Turner configuration is the Ebert-Fastie configuration, for which the two concave mirrors are combined into one large mirror.

The Rowland circle configuration is still widely used. Here, the setup includes the entrance slit, the grating and one or more exit slits or point detectors. This enables the spectrum to be polychromatically measured through the simultaneous measurement of intensity at several points on the Rowland circle. The holographic manufacturing method of aberration-corrected concave gratings enables a simple setup with entrance slit, diffraction grating and exit slit (constant-deflection monochromator) or line detector (flat field spectrograph).

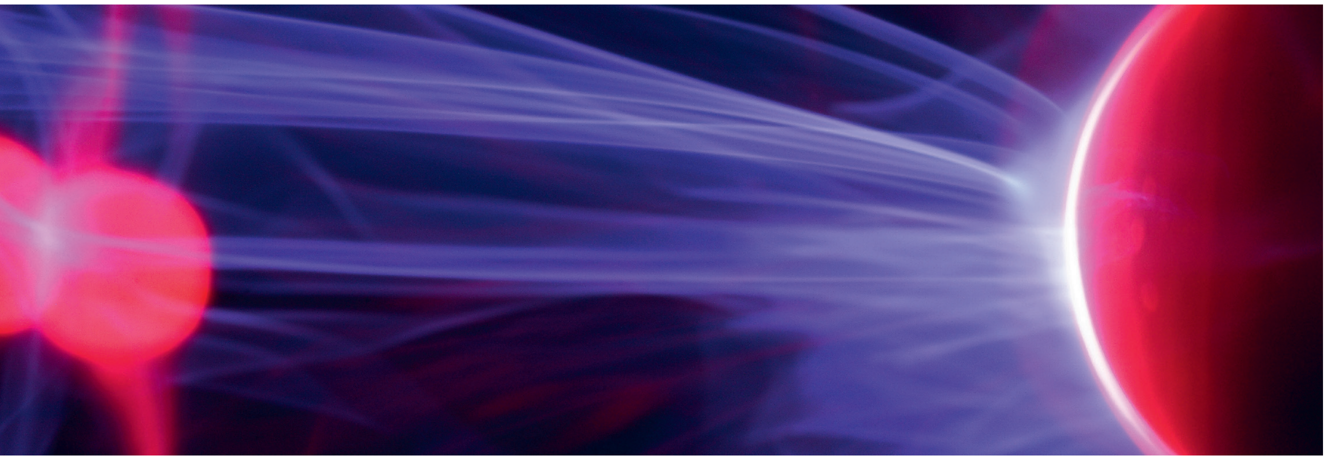

Fig. 41 Emission spectroscopy of gases in vacuum

With gratings on curved substrates, imaging spectrographs can also be constructed where every point of the entrance slit can be spectrally resolved on a flat detector. A configuration for such devices is the Offner spectrograph, which is, in principle, a Czerny-Turner spectrograph with a convex grating instead of a plane grating. This allows outstanding imaging properties and thus high spectral and spatial resolution.

Optical emission spectroscopy

In optical emission spectroscopy, the emitted radiation of excited atoms and molecules is examined. The excitation can be achieved through high temperatures or other methods that provide a lot of energy.

The wavelengths of the emitted radiation provide information on the composition of the examined specimen while the intensity yields information on the associated concentrations.

Emission spectra can be divided into three groups:

- Continuum spectra like those caused by glowing solid bodies. These do not result in distinguishable spectral lines.
- Band spectra like those caused by molecules. In general, these are highly widened spectral lines.
- Line spectra like those emitted by excited atoms. In general, the discrete and well-defined lines permit clear allocation.

The following methods are usually used for excitation.

- Flame: Flame emission microscopy (FES)
- Plasma: inductively coupled plasma optical emission spectroscopy (ICP-OES) or microwave plasma torch optical emission spectroscopy (MPT-OES)
- Light arcs/sparks: emissions from a light arc or generated sparks
- Exposure: optical fluorescence spectroscopy (OFS)
- Glow discharge: glow discharge optical spectroscopy (GDOS)

Both monochromators and polychromators can be used to analyze the radiation.

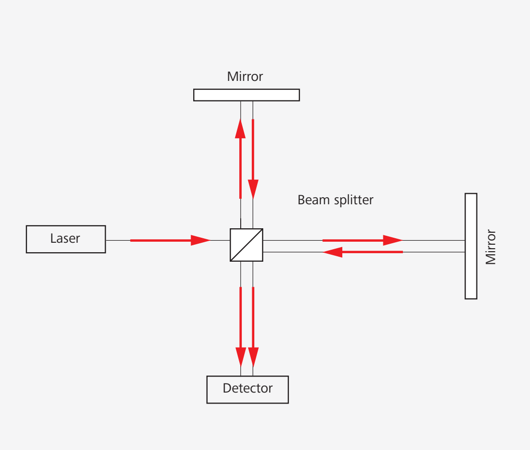

Fig. 41 Michelsen interferometer

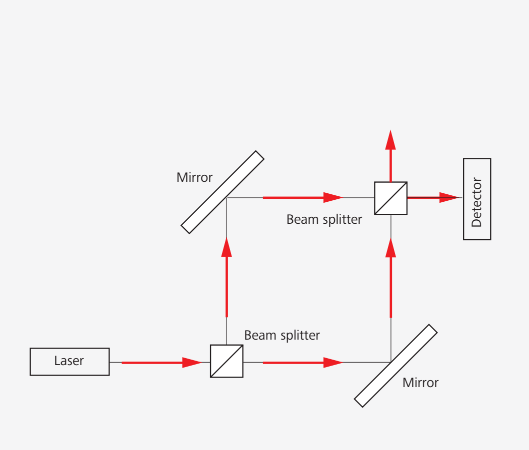

Fig. 42 Mach-Zhender interferometer

Molecular spectroscopy

Molecular spectroscopy is used to measure the interaction between molecules and electromagnetic radiation. It enables examination of molecular properties such as bond lengths and strengths, as well as atomic components. Unlike atom spectra, molecule spectra exhibit considerably more lines that usually overlap. The lines are the result of electron, vibration and rotation transitions in the molecule which lead to the absorption or emission of radiation. Accordingly, they can be examined through emission and absorption spectroscopy.

The following optical methods belong to molecular spectroscopy:

- Frequency modulation spectroscopy
- Fluorescence spectroscopy
- Vibration spectroscopy in the form of IR and Raman spectroscopy
- UV/VIS spectroscopy

As with optical emission spectrometers, molecular spectroscopy uses monochromators and polychromators. In the lab environment for IR spectroscopy FTIR spectrometers are frequently used.

Non-optical methods of spectroscopy include:

- Magnetic resonance spectroscopy
- Electron spin resonance spectroscopy
- Microwave spectroscopy

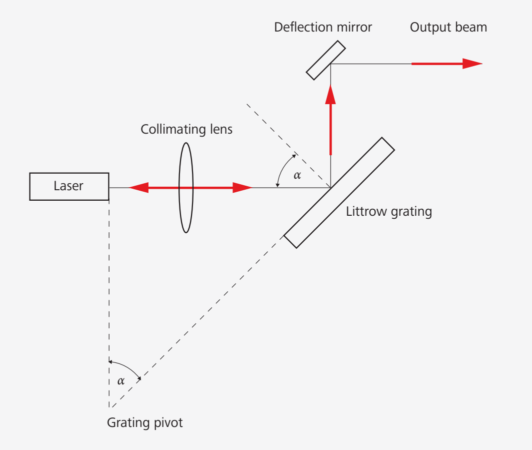

Fig. 44 Littrow configuration

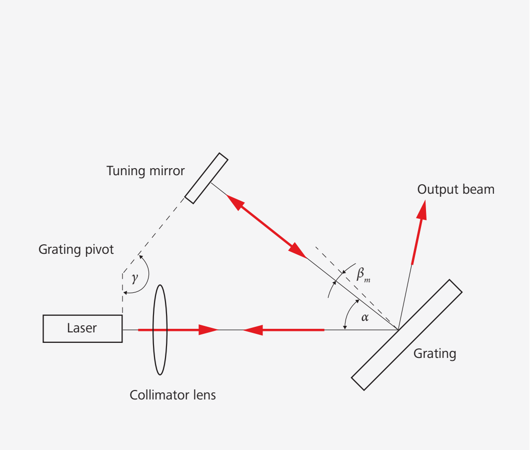

Fig. 45 Littmann configuration

Laser adjustment and laser stabilization

The active media of very many lasers, e.g. laser diodes, titanium-sapphire or dye lasers can have rather broad gain bandwith. However, it is not always desirable for the laser to operate over the entire band width simultaneously. A dispersive element integrated into the resonator can be used to adjust the wavelength emitted by the laser. Alternatively, part of the decoupled radiation can be fed back into the resonator, selected by its wavelength. Therefore, it is common to place a grating at the exit of a laser diode. Then, the zero order is used for the actual application, while the first order is used for wavelength selection via feed back. This can be done either by diffracting the first order directly (Littrow configuration) or via a mirror, and from there recoupling it into the resonator via the grating (Littmann configuration). The benefit of the more complex Littmann configuration is that the mirror and not the grating is adjusted and the direction of the application beam does not change when the laser is tuned. As a result, the wavelength of a wide-band laser can be selected or a laser stabilized in a mode of its discrete mode spectrum.

For stabilization of a broadband laser to exactly one mode, an additional narrow-band filter such as a Fabry-Perot-Etalon filter may be necessary. Because the free spectral range of such filters is also usually very narrow, a grating is often used to preselect the spectral range.

Laser pulse shaping

For many applications, e.g. in medicine, molecular spectroscopy or materials processing, lasers with short, high-intensity pulses are needed. In most cases, these high-energy pulses are generated with the chirped pulse amplification (CPA) method. The reason for its use is that powers in the petawatt range (~ 10^{15} W) are needed in the pulses. These high powers cannot be generated directly as they would destroy most laser amplification media. Therefore, the pulses are delayed (i.e. stretched) outside the amplifier, which strongly reduces the energy density. After amplification, the pulses are re-compressed which results in the high power density needed for the respective application. Because pulses have a broader wavelength spectrum the shorter they become, very short pulses can also be easily stretched and compressed again by strongly delaying different wavelengths

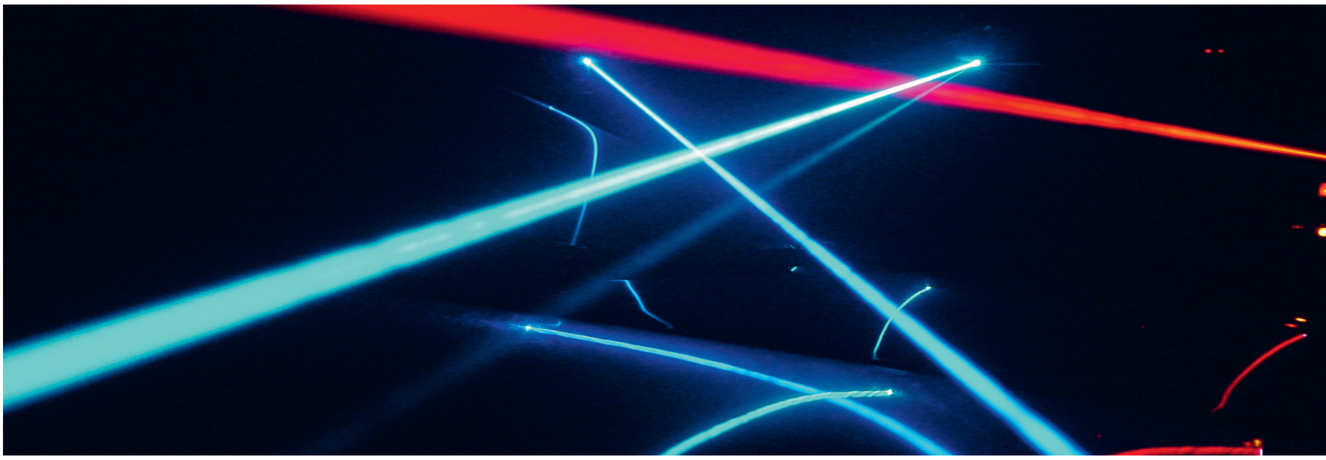

Fig. 46 Laser tuning and laser stabilization

to varying degrees. Highly-efficient gratings are therefore ideal for stretching pulses for amplification and then compressing them again.

Further applications

Gratings are also occasionally used for, e.g. beam splitting and as setting gauges.

Beam splitting

Splitting a light bundle into two or more usually interference-capable partial bundles is described as beam splitting. The most commonly used method of splitting light rays is the use of partly reflecting surfaces on an otherwise transparent substrate. This splitting is then approximately wavelength-independent and is described as division of amplitude. The required components are partially or semi-permeable mirrors, plate beam splitters or cubic beam splitters. However, division of amplitude can also be performed by gratings by using the different diffraction orders of an incident light beam as split beams. This beam splitting plays a key role in interferometers for the precise determination of lengths, wavelengths, refractive indices and the form of surfaces. The most important basic forms of such interferometers are the Michelson and the Mach-Zehnder interferometer, on which gratings are used as beam splitters.

Setting gauge

The high accuracy of the groove density of holographically manufactured gratings can be used for the manufacture of setting gauge. Therefore, errors of $< 0.1\ \text{mm}^{-1}$ of the groove density from the nominal value can be achieved. High-frequency gratings can thus be used as resolution gauge. Furthermore, the profile depth of gratings can be very accurately set between 100 nm and 50 µm. Therefore, gratings are occasionally ideal as depth setting standards.

The moment you know that experience
and know-how are irreplaceable.
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