

Fused Silica Transmission Gratings

A White Paper

Kristian Buchwald
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History

Diffraction gratings have been manufactured for over 200 years, with developments being driven initially by requirements of spectroscopy, where gratings have been applied ever since Joseph Fraunhofer's work in the early 1800's. For many years, grating production remained the realm of high-precision instrument makers – builders of one-of-a-kind complex ruling machines that manually scratch away material from a blank substrate to produce master gratings. As this mastering technology is very time-consuming and thus expensive, commercial gratings have mainly been replicated gratings – gratings that are copied in high quantities from the master form into a polymer. This technology in practice allows only for reflection gratings where the polymer material is coated with a metal, as the polymer is of a low optical quality – unsuitable for transmission, and groove profiles for high efficiency transmission gratings are not possible by the ruling method. Metal-coated reflection gratings have thus “ruled” the world for centuries.

More recently, since the advent of the laser, the ruling technology has been superseded in quality-demanding applications by holographic patterning, which has improved grating performance on important points as resolution and stray-light.

Over the past decades, semiconductor technology has appeared and matured, offering manufacturing technologies applicable to transmission gratings, and bringing with it the high-volume low-cost benefits of semiconductor technology. By combining recent strides in production-oriented holographic patterning technology with semiconductor material and etching technologies, it is today possible to produce transmission gratings, etched into fused silica, that rival reflection gratings in all aspects.

Fundamentals

Grating types

Gratings can be classified in a multitude of different ways. The main classifications for free-space gratings, together with relevant characteristics and examples are given below. It is important to note that for all grating types, the grating equation alone determines the geometric diffraction properties of the grating – the various types of gratings solely affect diffraction efficiencies and therefore each have their own areas of suitability.

A fundamental distinction can be made between **amplitude gratings** and **phase gratings**. An example of an amplitude grating is a lithographically patterned Cr-on-glass grating, in which the Cr lines reflect light while the openings transmit light. This grating type has fundamentally limited efficiency and is therefore not widely used today. Rather than blocking light, the phase grating works by altering the phase of the light in two (or more) levels within each grating period. This enables full use of the light, thereby avoiding the fundamental limitation on diffraction efficiency.

Another important distinction is between **reflection gratings** and **transmission gratings**. While reflection gratings diffract light back into the plane of incidence, transmission gratings diffract the light into the opposite half-space. Where gratings are used to provide retro-reflected feedback (i.e. gratings for external laser cavities), reflection gratings are often preferred, whereas transmission grating-based geometries are ideal for most other optical designs (for example spectral separation or beam-splitting) where a spatial separation of input and output is preferable.

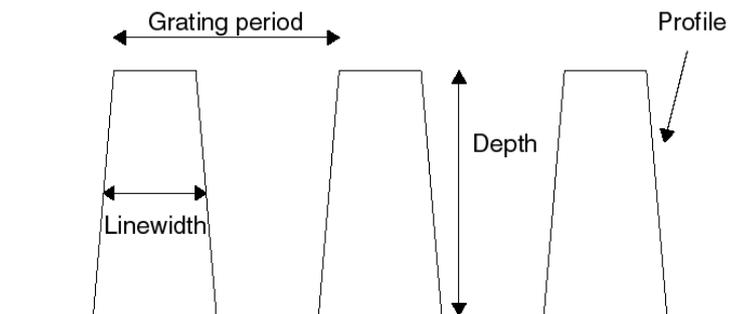
As described above, phase gratings work by imposing periodic phase changes on the light that illuminates the grating. The phase of the light can be manipulated with physical grating corrugations – in which case the grating is called a **surface relief grating**. Conventional reflection gratings are surface relief gratings, where the phase is altered by periodic changes of the physical distance that the illumination experiences from grating top to grating bottom. Fused silica transmission gratings are also surface relief gratings, where the phase is altered by periodic changes of the optical distance that the illumination experiences as it passes through the grating material versus air. Fused silica gratings work with a large difference in refractive index between air ($n=1$) to fused silica ($n\sim 1.5$.) Alternately to surface relief gratings, the phase change can be imbedded in the grating material itself, in which case the grating is termed a **volume phase grating**. Such gratings work with a low variation in the refractive index in the grating material, and so these gratings typically must be thick to provide high efficiency. As a consequence of this, volume phase gratings generally have high wavelength and angle sensitivity, while fused silica transmission gratings have high wavelength and angle tolerance.

Of mostly historic importance, gratings can be **ruled** or **holographically** patterned. Today, holography has all but displaced ruling technology for high-performance gratings, due to higher resolution capability, lower stray light and much more efficient production. A few other patterning methods have found niche applications – laser-write and e-beam patterning which are mainly used in the broader field of diffractive optics to pattern complex elements (e.g. computer generated holograms), but which lack the production efficiency, phase stability etc required by most diffraction grating applications.

There is finally a strong distinction between **master gratings** and **replicated gratings**, where replicated gratings are produced using a master grating as a mould. Conventionally, the benefit of the master grating has been higher grating quality as the fidelity is reduced in any copying process, while the benefits of replicated gratings have been more repeatable gratings (insofar as the same master is used and does not deteriorate) and lower cost. A recent production technology – holographic stepper technology – breaks this distinction, as the

gratings fundamentally are holographically patterned masters, but produced with a high-volume production technology similar to semiconductor steppers, which are well known for their high repeatability and high volume cost efficiency.

Physical parameters



A surface relief grating can be described by the following parameters, with reference to the drawing above:

- The **grating period** is defined as the distance between the many, equally spaced grating grooves (or grating lines). The inverse of the grating period is the **grating resolution**, typically given as the number of grating lines per mm.
- The **depth** of the grating is the distance from the top of the grating grooves to the bottom of the grating grooves. In the case of fused silica transmission gratings this is often called the etch depth.
- The **duty cycle** of the grating is defined as the linewidth divided by the grating period.
- The **aspect ratio** of the grating is defined as the ratio between the depth and the width of the grating groove (grating period – linewidth). A high aspect ratio describes a deep grating groove.
- The **grating profile** is a general term for the shape of the grating grooves, which could be rectangular, sinusoidal, trapezoidal or more complex, in each case being quantifiable by additional parameters that will not be described here.

Grating properties

Diffraction

While in fact intertwined, gratings have 2 features that at first glance seem unrelated. The first feature is that a grating will split up (diffract) an incoming laser beam into multiple, discrete beams. The second feature is that a grating will angularly separate (disperse) the wavelengths of a non-monochromatic light source (similar to the prism). Both these features are governed by the important grating equation:

$$m \cdot \lambda = \Lambda \cdot (\sin \theta_I + \sin \theta_D),$$

where:

m is the m'th diffraction order

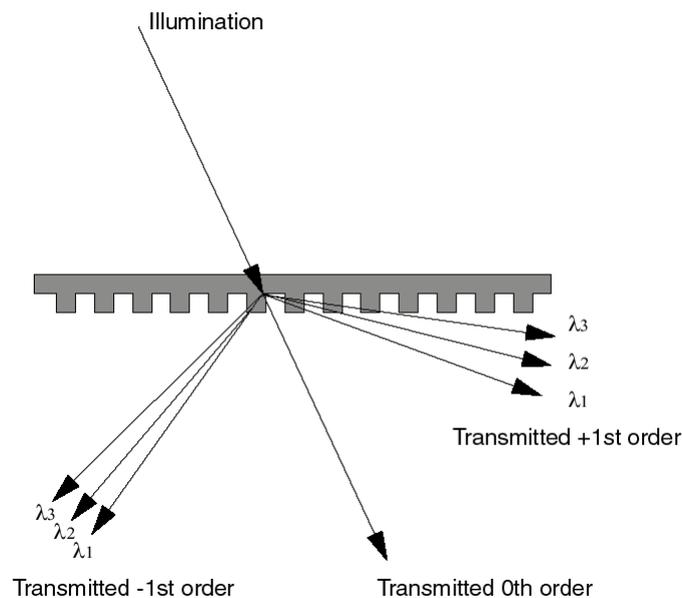
λ is the wavelength of the illumination

Λ is the grating period

θ_I is the incidence angle of the illumination

θ_D is the diffraction angle of the illumination for the m'th diffraction order,

all with respect to the following schematic:



Beam splitting

As fully described by the grating equation, a grating has a beam splitting property, in that a laser beam – or other monochromatic light source – will be split into the multitude of diffracted orders – the number of which is given by the values of m that have real solutions to the grating equation.

Normal incidence is an often used configuration for beam splitting applications, as there is perfect symmetry in the first order diffraction angles. At normal incidence the grating equation is reduced to:

$$m \cdot \lambda = \Lambda \cdot \sin \theta_D$$

Furthermore, if the grating profile is symmetric (a feature of fused silica transmission gratings), diffraction efficiencies in the symmetric orders is therefore also achieved. In this way, a highly effective and balanced beamsplitter is the result, furthermore with polarization dependence or independence that can often be designed as required.

Another configuration often of special interest is the special case where the diffraction angle of the -1 order is equal to the incidence angle. This is known as Bragg or Littrow configuration, and the grating equation in this case is reduced to:

$$\lambda = 2 \cdot \Lambda \cdot \sin \theta$$

The significance of this configuration becomes apparent especially when the following equation is fulfilled:

$$\frac{2}{3} \leq \frac{\lambda}{\Lambda} \leq 2$$

When this equation is fulfilled, only the 0 and -1 orders will be transmitted, and thus a second type of highly efficient beamsplitter has been devised.

Dispersion

A grating's ability to separate the wavelengths of an illumination is known as **angular dispersion**. The angular dispersion is given by the following equation:

$$\frac{d\theta_D}{d\lambda} = \frac{\sin(\theta_I) - \sin(\theta_D)}{\lambda \cdot \cos(\theta_D)},$$

where θ_D is given by the grating equation, which shows the dependence on illumination wavelength, grating period and incidence angle.

A high dispersion means that there is a high angular separation between the diffracted wavelengths, which translates to a high resolution or compact design of an optical system. (Note that the resolution of an optical system (specified in e.g. nm) and the resolution of a grating (specified in lines/mm) are two different things.)

A high dispersion is achieved from a high grating resolution (corresponding to a low grating period).

Diffraction efficiency

The amount of light that a grating directs into a specific direction – or diffraction order – is termed **diffraction efficiency**. Diffraction efficiency of a grating is not easily predicted; while grating manufacturers/users often will develop a certain intuition based partly on simplified physical models, precise prediction of diffraction efficiency can only be calculated by solving the set of Maxwell equations for the given illumination combined with upheld boundary conditions of the given grating.

Diffraction efficiency is defined as the proportion of the incident light that is present in a specific diffraction order. This is also known as **“absolute diffraction efficiency”**. This is important to note, as metal-coated reflection gratings often state diffraction efficiency relative to the reflection of a metal mirror. While this may be convenient for manufacturers due to convenience in metrology, it leads to deceptive values of diffraction efficiency, as metals have always some and often significant loss.

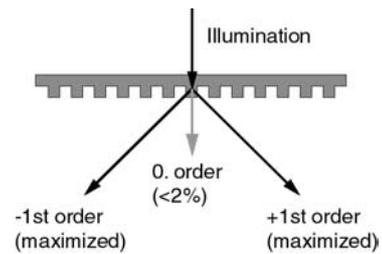
Fused silica transmission gratings can be optimised for numerous diffraction efficiency requirements, some important examples of which will be described below. In all cases, this optimisation of a specific fused silica transmission grating involves designing the grating's duty cycle, depth and profile for the given grating period and illumination (bandwidth and polarization).

Here are a few important diffraction efficiency optimisation possibilities:

- **Equal +1 and –1 orders with normal incidence illumination**

This is a widely used beam-splitter configuration, diffraction angles are well defined and diffraction efficiency in the first orders is very well balanced through the inherent symmetry in fused silica transmission gratings.

For a given illumination wavelength the diffraction angle of the first orders is given by the grating period via the grating equation.



Such a grating is optimised to direct maximal efficiency into the first orders, while suppressing the 0. order to a minimal level. The 0. order can typically be suppressed down to below 2%, a performance that is achievable as a rule of thumb so long as the grating period is more than twice the wavelength, i.e. $\Lambda > 2 \cdot \lambda$. In this situation, and even more so as the ratio between Λ and λ further increases, the diffraction efficiency is also quite insensitive to the polarization of the illumination.

This grating type is a special and interesting case in that an intuitive model to understanding the 0. order suppression is at hand. Assuming a 50% duty cycle one can view the illumination as being passed 50% through the grating ridge and 50% through the grating valley. In order to cancel the (far field) 0. order, these 2 equal contributions should be perfectly out of phase – a criteria that is fulfilled when the difference in optical distance through the grating ridge material (fused silica) and the grating valley material (air) is exactly equal to half a wavelength. In equation form this can be expressed as:

$$n \cdot \text{depth} - \text{depth} = \frac{\lambda}{2}$$

⇒

$$\text{depth} = \frac{\lambda}{2 \cdot (n - 1)}$$

, where n is the refractive index of the grating material. With an approximate value of this refractive index for fused silica of 1.5, this equation reduces to the very simple:

$$\text{depth} = \lambda$$

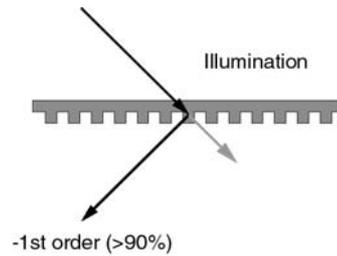
While intuitively simple, note that this is only a scalar model that does break down when the illumination wavelength is only a few times higher than the grating period.

This beam-splitter type is extensively used by manufacturers of fiber Bragg Gratings (FBGs) under the name “+/-1 order Phase masks”.

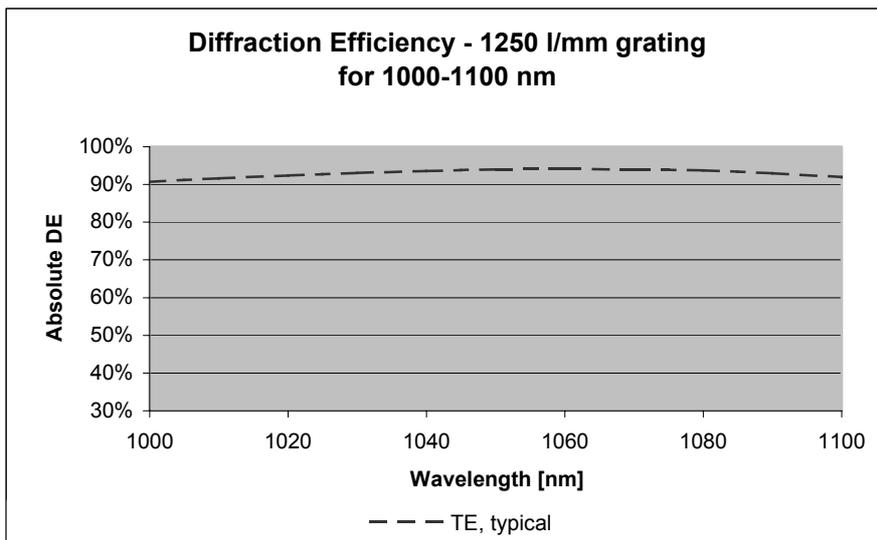
- **Maximum -1 order with off-normal incidence illumination**

This is a grating configuration that is used to generate dispersion. Depending on the application there may be different criteria for optimisation.

In one application the bandwidth of the illumination may be small (e.g. in the case of a laser); in this case the illumination angle may advantageously set at Littrow angle illumination, with a grating period chosen so that the Littrow angle is 30° or 45°, in which case fused silica transmission gratings can be optimised to provide > 90% efficiency. This can be achieved with conventional fused silica grating technology for a single polarization, or with unique (and proprietary) Ibsen PING (Polarization independent grating) technology for both polarizations simultaneously.

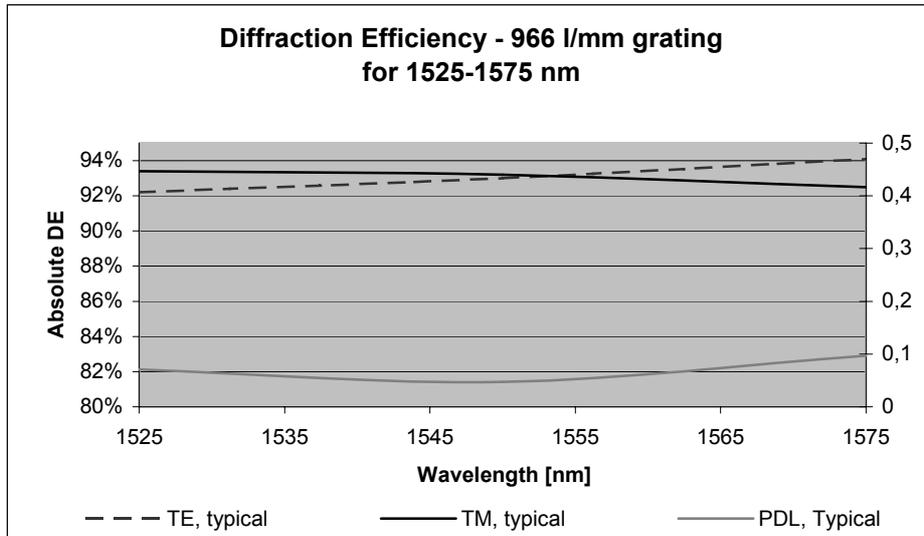


Below is shown a typical diffraction efficiency spectrum of a conventional fused silica pulse compression grating – the specific grating is a 1250 l/mm grating, optimized for 1064 nm illumination.



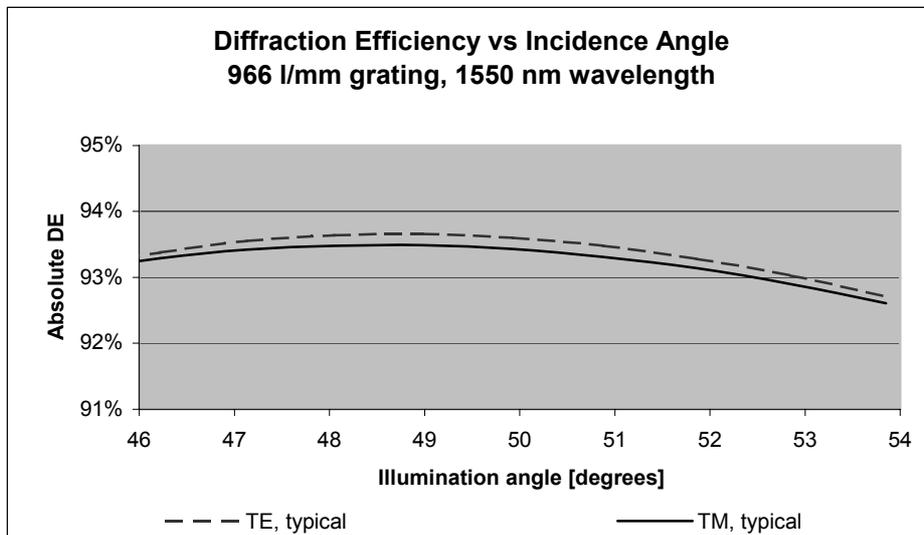
Theoretically, very close to 100% diffraction efficiency can be achieved, and individual specific gratings also can come very close to this theoretical limit. In practice, >90% is a level that is possible to consistently achieve in commercial products allowing.

The following plot shows a typical diffraction efficiency and PDL (polarization dependent loss) spectrum of a polarization independent grating – the specific grating is a 966 l/mm grating, optimized for telecom C-band illumination.



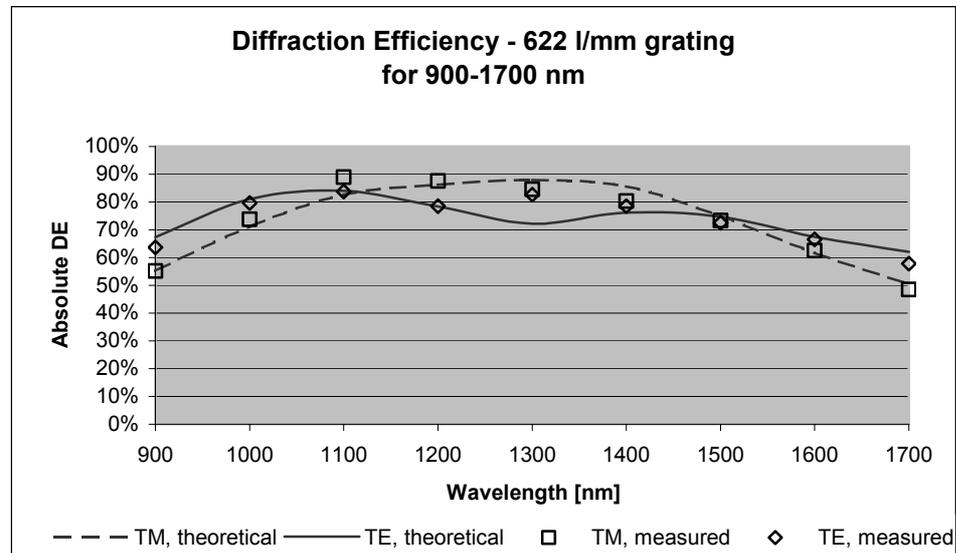
As with the previously shown grating, again it is possible to achieve very close to 100% diffraction efficiency of individual, specific gratings, and possible to offer >90% efficiency in commercial products.

An interesting characteristic of fused silica gratings is their high tolerance to the incidence angle of the illumination. This is illustrated in the following plot, which shows the efficiency of the above grating as a function of incidence angle.

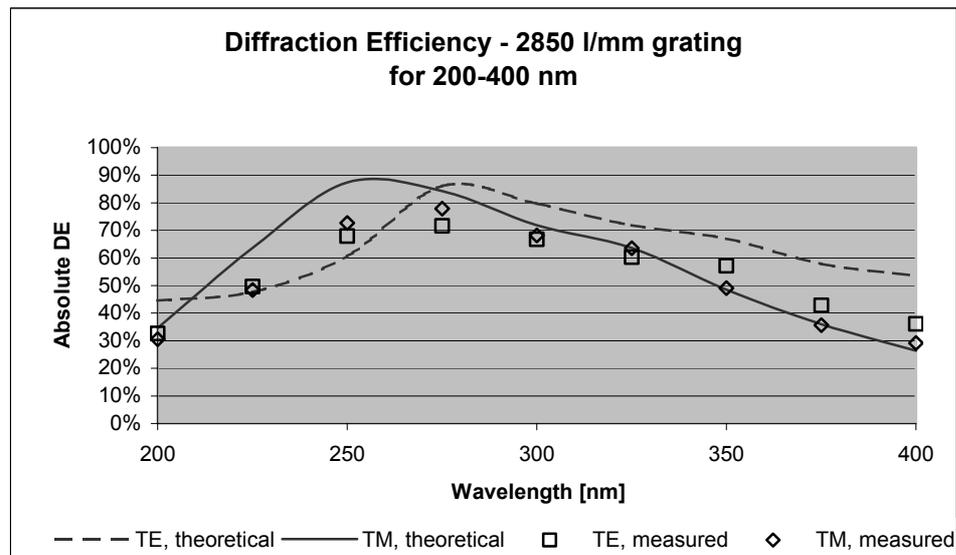


In other applications the illumination bandwidth is large, for example typical spectrometer applications where the bandwidth is on the order of one wavelength octave (i.e. the longest wavelength in the bandwidth is double the lowest, e.g. 200-400 nm, or 550-1100 nm.) While conventional reflection gratings are most efficient in providing high efficiency with low dispersion gratings, fused silica transmission gratings are most efficient in providing high efficiency, high dispersion gratings. A rule-of-thumb to get the best of a fused silica transmission grating is to choose a grating period that is toward the upper end of the bandwidth (e.g. for a bandwidth of 800-1600 nm, a good choice of period is 1500 nm, corresponding to roughly 650 l/mm), and designed for an illumination incidence angle of 20-30°. For such a grating, a typical minimum efficiency of >50-60% for unpolarized light, across the full

bandwidth, can be achieved. An example of such a produced fused silica grating is shown below, with theoretical and actual performance:



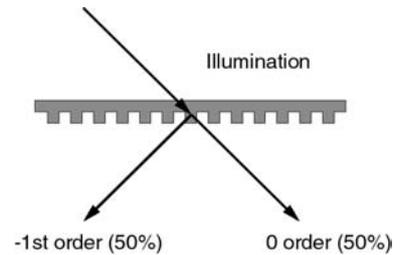
Another example, a UV grating, is shown in the following plot:



- **Equal 0 and -1 order with Bragg (Littrow) angle incidence**

This is another beam-splitter configuration, in which diffraction angles are well defined and diffraction efficiency in the first orders is balanced between the 0. order and the -1 order through the optimisation of the grating.

While not an explicit requirement, the incidence angle is often chosen to be Bragg (Littrow), in which case both the 0. order and -1 order diffraction angle will be Bragg also.



This grating configuration is especially useful in the earlier mention case of

$\frac{2}{3} \leq \frac{\lambda}{\Lambda} \leq 2$, as such a grating will exhibit no other diffraction orders than the 0 and -1 order.

This beam-splitter type grating is known by DFB laser manufacturers (and other waveguide grating manufacturers that write grating periods below a few hundred nm) as “0/-1 order Phase masks.” Diffraction efficiency in the range 40..60% in each order is typically required and can be achieved.

For all fused silica transmission gratings, it is a typical characteristic that diffraction efficiency is very tolerant to variations in the incidence angle of the illumination.

Grating materials

Almost as important as the distinction between the fundamental types of grating (amplitude vs phase, transmission vs reflection, surface relief vs volume phase, ruled vs holographic and master vs replicated) is the choice of grating material. A brief overview of commercially available grating types is given below, with a detailed listing of material properties given only for fused silica transmission gratings. The list is given in order of historic appearance.

Conventional reflection gratings

Conventional reflection gratings are composed of a substrate material (typically a glass), an epoxy or photoresist into which the grating is profiled, and finally a metallic coating on top. It is often the epoxy/photoresist that limits the environmental and thermal stability of the grating, while it is the metallic coating that is the basis for the grating's optical performance and power handling limitations.

Dichromated gelatin (DCG) gratings

DCG gratings are volume phase gratings, with the grating formed inside a DCG material, which has been deposited on a substrate. A DCG grating typically has the DCG sandwiched between 2 substrates (glass or fused silica) and with the edges sealed, as the DCG material is environmentally instable. The DCG material is also the limiting factor with regards to thermal stability.

Multilayer dielectric (MLD) reflection gratings

MLD gratings are surface relief gratings, typically etched in fused silica, on top of a reflective dielectric stack as known from standard reflection coatings. This grating type has many material properties in common with fused silica transmission gratings and can be regarded as a reflective counterpart to the fused silica transmission grating.

Fused silica transmission gratings

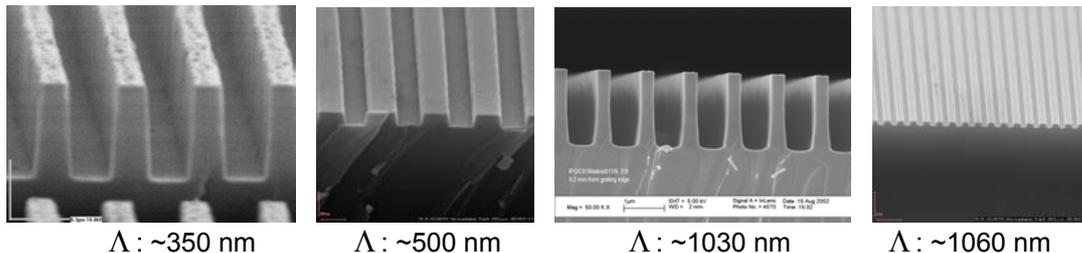
Fused silica transmission gratings are 100% fused silica, when required with the addition of a backside dielectric antireflection coating. Fused silica is an ideal grating material for many reasons, and boasts the following properties (Appendix A gives a quantitative overview of important, physical properties of fused silica material):

- Fused silica has a broad transmission spectrum, making fused silica suitable for a wavelength range spreading from below 200 nm (fused silica can be modified to extend down to 157 nm) and up into the mid infrared.
- Across a very broad bandwidth from the UV to NIR, the absorption of fused silica is insignificant – fused silica is perhaps the most transparent material known. This is an important fact when considering grating materials for high power applications, as for example the metal coatings of conventional reflection gratings have magnitudes higher absorption than fused silica, typically absorbing percentage points of the incident energy.
- Fused silica is physically stable, and does not react with the environment. Where DCG is hygroscopic, and metals oxidize, fused silica is impervious to most environmental challenges. Similarly, fused silica has a practically unlimited lifetime, unlike gelatins and epoxies that degrade over time, accelerated by heat and UV exposure.
- Fused silica can be used at temperatures at a level of 1000 °C, much higher than epoxies and gelatins.

Metrology

Profilometry

As the grating profile has great impact on diffraction efficiency it is important to have knowledge of this. With grating periods typically in the range 200 –2000 nm, fused silica gratings are advantageously examined with AFM/SEM. AFM (Atomic Force Microscopy) has the benefit of providing quantitative measurements, while SEM (Scanning Electron Microscopy) has the advantage of giving a true “visual” image of the grating. Below are a few SEMs of fused silica gratings, illustrating typical grating periods, depths and profiles.



Grating period

Grating period can be measured through profilometry as described above. The accuracy of AFM/SEM metrology is often on the order of percent.

When precise grating period knowledge is needed, optical metrology is required. Grating period measurement systems are not commercially available, so one must build such metrology equipment when required. The grating equation provides a fundamental relationship between grating period, illumination wavelength and the angles of illumination and diffraction, so with a very precise laser source and a well-designed and controlled set-up, it is possible to measure grating period with an accuracy of +/- 0.01 nm.

Diffraction efficiency

Diffraction efficiency is given for a specific wavelength, polarization and illumination angle of incidence in a specific diffraction order. A versatile measurement system (again, such systems are not commercially available) must therefore be able to vary illumination wavelength and polarization as well as the position of one or more detectors to measure the diffracted light. Note that the system should also be able to measure the illumination incident on the grating, so that true absolute diffraction efficiency can be measured.

Defects & stray light

Wafer inspection / defect inspection systems can be used to evaluate grating defects. A versatile system is able to inspect for grating defects over the full grating area, and provide a histogram of defect sizes and quantities.

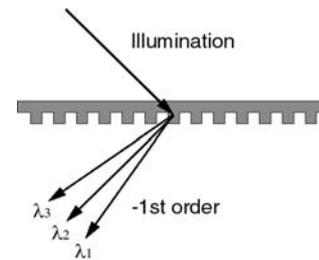
Defects, as well as a multitude of other grating artefacts, can cause scattered light from the grating. With care, angle resolved scattered light can be accurately measured; more commonly though scattered light is described by the term stray-light, which is taken to be the stray-light measured in a particular instrument. This is a pragmatic approach to stray-light, as such a measurement also will take into account the instruments' handling of other diffracted orders from the grating. When possible it is therefore often most beneficial to evaluate stray light of a grating in the actual optical system that the grating will be used in, and care should be taken to avoid misinterpretation of stray light caused by other apertures, reflections or otherwise within the optical system.

Applications

Spectrometry

Spectroscopy was one of the earliest applications of gratings, and it remains one of the main grating uses. Most spectrometers today are based on reflection grating designs, as high quality transmission grating technologies have only matured over the last several years.

The principle of operation of a spectrometer grating is shown at right. The incident illumination is diffracted in the grating and the wavelengths are dispersed leaving the grating.

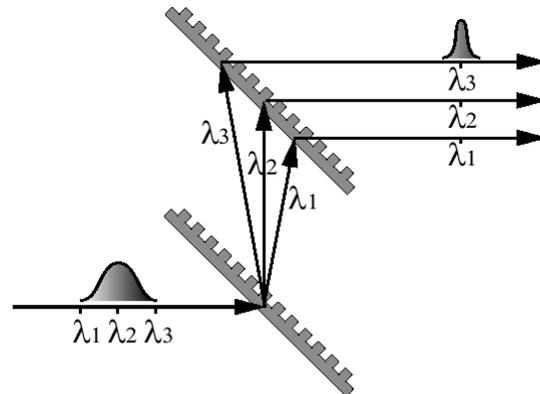


For many spectrometer designs, transmission gratings offer a number of benefits:

- Reflection gratings fundamentally diffract the dispersed light back into the plane of incidence – often directly back into the quadrant of the incoming illumination. With transmission gratings, the output plane is on the opposite side of the grating from the input plane, thus easing the design process.
- Somewhat related to the above, a transmission grating can be utilized simultaneously as a dispersion generating element and a beam-folding element, allowing compact designs.
- Transmission optics impose less stringent requirements to angular alignment precision in the assembly, as misalignment of a reflective optic doubles the alignment error, while a transmission grating reduces the alignment error.
- Related to the above, transmission optics give rise to very little wavefront error in comparison to reflection optics.
- For low dispersion applications, reflection gratings are preferable as efficiency can be maximized efficiently for low grating resolutions. Fused silica transmission gratings oppositely can be made highly efficient mainly for higher resolution gratings than the reflective counterparts.
- In many cases fused silica transmission gratings will offer higher, more broadband efficiency than comparable reflection gratings, and without spectral anomalies such as Wood's anomalies that metal-coated reflection gratings suffer from.
- Fused silica transmission gratings are produced by holographic patterning and RIE etching; both are high-fidelity processes that offer low stray light of the gratings.
- Finally, holostepper grating production technology offers both the quality of master gratings as well as the repeatability and high volume production capabilities of replicated gratings.

Laser pulse compression

Another type of grating that is based on the dispersive property of gratings is the pulse compression grating. Using an identical grating pair, a temporally chirped pulse is dispersed in a first grating. The second grating recollimates the wavelengths, which due to the dispersion from the first grating have traveled different distances, with the long wavelength end having traveled further and therefore been delayed while the short wavelength end of the bandwidth has caught up.

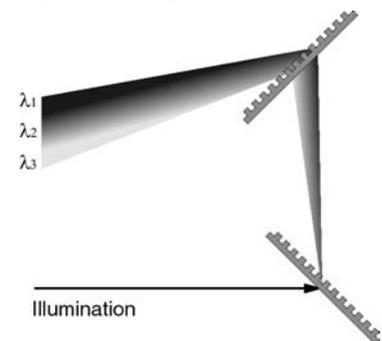


A main benefit of 100% fused silica transmission gratings is that no other materials boast the same power handling capabilities as fused silica. As power requirements increase, this benefit is gaining importance as the conventionally utilized metallic reflection gratings reach their limits and break down.

Telecom gratings

A specialized, dispersive grating is the telecom grating – basically a narrow-band spectrometer grating. In telecom DWDM (Dense Wavelength Division Multiplexing) networks, free-space optical modules utilize diffraction gratings as demultiplexers, either for demultiplexing units, or as the initial component in ROADM (Reconfigurable Optical Add Drop Modules), DGFF (Dynamic Gain Flattening Filters) or DC (Dispersion Compensation) modules. This application is characterized by a requirement for high dispersion within a narrow bandwidth (for example 1525-1575 nm), and with extremely demanding requirements to diffraction efficiency and polarization independence. Fused silica grating technology has been applied to this application, and have achieved gratings with 95% DE and 0.05 dB PDL (Polarization Dependant Loss). Being 100% dielectric, these gratings are furthermore ideal with respect to Telcordia requirements, as they contain no polymers, glues or epoxies.

The diagram to the right depicts a 2-grating design (US Patent 6,978,062), which effectively provides twice the dispersion of a single grating while simultaneously conveniently folding the beam path to make efficient use of the module footprint. At the exit plane, a diode array, MEMS device, liquid crystal device or similar would measure or manipulate the dispersed wavelengths. Fused silica gratings are notably appropriate for this design due to the high angle tolerance of fused silica transmission gratings.

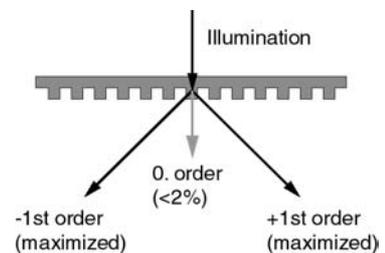


Phase masks / beam-splitters

The grating applications described above all utilize the dispersive property of gratings. As gratings also have the property that a discrete wavelength illumination will be diffracted into several discrete diffraction orders according to the grating equation – beam-splitting applications of gratings also abound. Transmission gratings’ high power handling capabilities and environmental stability, combined with the possibility of grating periods down to 200 nm, make fused silica transmission gratings ideal for space, astronomy and scientific applications.

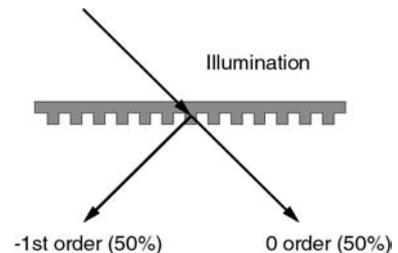
A well-known example of a beam-splitting grating is the Phase mask, a diffractive tool used in the manufacture of fiber Bragg gratings and waveguide gratings. The use of for example 193 nm and 248 nm excimer light sources benefits from the UV transmission properties of UV grade fused silica.

Phase masks of the +1/-1 order principle utilize one of the optimization possibilities mentioned earlier – maximization of the +1 and –1 transmitted orders while simultaneously minimizing the 0. order. The diffracted beams below the Phase mask interfere; the resulting interference pattern has precisely half the period of the Phase mask, and can be recorded by photosensitivity into a medium placed below the Phase mask.



The +1/-1 order Phase mask principle is primarily used to write gratings directly into photosensitive silica fibers.

Phase masks of the 0/-1 order principle utilize another of the optimization possibilities mentioned earlier – a balance of the 0 and –1 transmitted orders. The diffracted beams below the Phase mask interfere; the resulting interference pattern has precisely equal to the period of the Phase mask, and can be recorded by photosensitivity into a medium placed below the Phase mask.



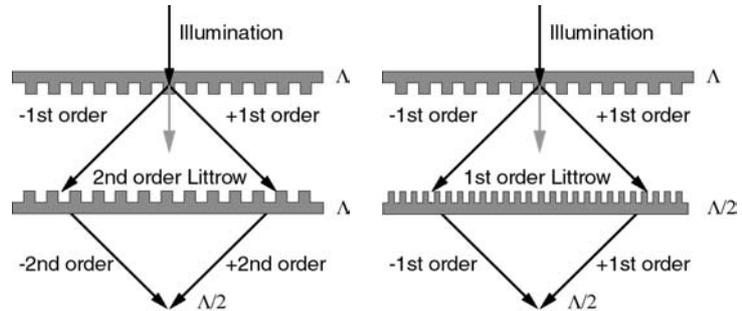
The 0/-1 order principle is primarily used to write gratings into photoresist, as even a small 0. order from the +1/-1 order principle Phase mask can be problematic when recording in photoresist. The 0/-1 order principle is furthermore especially useful when writing grating periods that are less than twice the illumination wavelength, as the +1/-1 order principle becomes unsuitable due to impossibility of suppressing the 0. order.

For both types of Phase masks, the Phase mask is basically functioning as a beam-splitter, which, being placed in the immediate proximity of the recording medium, provides a stability in the interferometry that is practically unachievable in a conventional 2-beam holographic set-ups.

Phase masks can furthermore be produced with 2D grating periodicities. Such 2D Phase masks can just as the 1D Phase masks described above replicate their grating periodicities onto a photosensitive material, for example for printing 2D photonic bandgap (PBG) structures. In comparison with making two serial 1D exposures perpendicular to each other, the 2D Phase mask approach has the benefit that the resulting pattern has full resist height surrounding the 2D array of “holes”, in addition to being a one-step process.

Achromatic grating interferometer

This application – well described in the literature – is related to the Phase mask, in that this 2-grating interferometer's function is to create an interference pattern that is defined by a master grating (Phase mask). The complexity of using 2 gratings instead of a single accomplishes multiple things:



- The recombination at the interference point is light that came from the same spatial position on the first grating – in this way a low spatial coherence of the illumination is managed.
- This interferometer is therefore especially useful when using low coherent light sources, for example DUV (deep UV) light sources such as 193 nm excimer lasers. With low wavelength light sources, low grating periods can be generated, and with this interferometer sub-100 nm grating periods can be generated, aided further by working in immersion following the 2nd grating.
- Another illumination wavelength, while possible having different diffraction efficiencies, will still recombine with the same grating period at the interference point, hence the name for this interferometer: achromatic grating interferometer.

Production technology

This section describes the most important and distinguishing production processes used in the fabrication of fused silica transmission gratings. There are 2 such processes – the grating patterning in photoresist and the following transfer of the photoresist-based grating into fused silica. Grating patterning is accomplished by one of 2 technologies described below, followed by a brief description of the etching process.

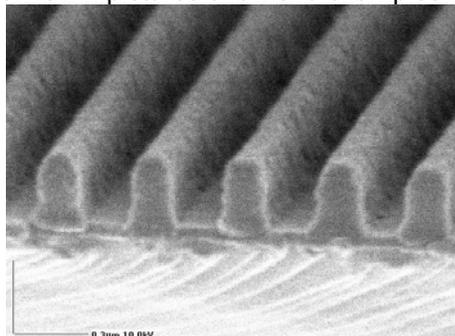
Conventional holography

The patterning of fused silica transmission gratings is often done using conventional holography, in which two coherent, collimated beams of light are brought to interfere at a plane in which a photoresist-coated fused silica substrate is placed.

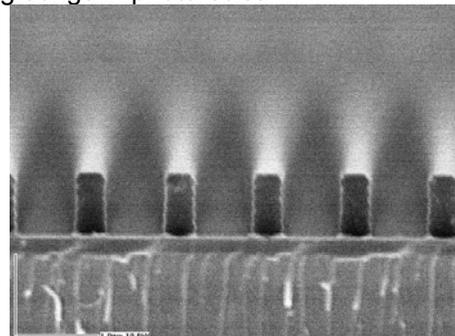
With tight control and precise metrology, gratings can be patterned with a grating period accuracy of 0.01 nm over large areas.

Following exposure, the photoresist is developed to leave grating lines defined in photoresist on the fused silica substrate.

The below SEM pictures show two examples of gratings in photoresist.



350 nm period grating in photoresist



1000 nm period grating in photoresist

Holographic stepper

Holography has typically been characterized by superb, noise-free quality, but with an Achilles heel in reproducibility. Ibsen has developed a holographic stepper that overcomes this limitation by combining the holographic principle with the stepper approach of semiconductor technology. In addition to a reproducible, high-yield process, this highly automated technique is ideal for a high-volume production process. The holostepper system has been utilized to produce gratings with resolutions from 450 to 3000 lines/mm.

The holographic stepper offers high quality grating patterning, and is integral to a high volume, low cost production process of fused silica transmission gratings.

It is important to realize though, that the holographic patterning techniques described above solely provide an intermediate product in photoresist. Photoresist – as any polymer – is both environmentally and thermally unstable, and therefore the ideal diffraction grating is polymer free. Replicated reflection gratings maintain the polymer material – as do volume holographic transmission gratings. What is needed is to transfer the high-quality grating pattern into a stable material, and this is where the semiconductor technologies come into play, notably the etching process described in the next section.

Fused silica etching

The grating pattern, exposed by conventional holography or holographic stepper, is transferred into bulk fused silica by semiconductor etching technology. Following the etch process, the grating is comprised of no further polymer material and is in fact a 100% dielectric component. Ibsen designs gratings and has developed etch technology that provides close to 100% diffraction efficiency even with high grating resolution. It should be noted that while most reflection grating manufacturers benchmark diffraction efficiency against a metal mirror which inevitably absorbs a few % of the illumination, transmission gratings in fused silica have fundamentally no absorption over a very broad illumination bandwidth that stretches from the deep UV to NIR.

Gratings thus manufactured in fused silica are both metal-free and polymer-free. Fused silica is widely recognized and used for its properties of superb environmental stability (including harsh temperature and humidity variations) as well as energy and power handling capabilities, and is as such the ideal material for optical components, including of course diffraction gratings.

The future is clear

Based on advances in holographic stepper technology and semiconductor processing, fused silica transmission gratings have begun displacing reflection gratings in grating applications new and old. This is achieved through meeting or even surpassing the performance of reflection gratings, combined with new standards for reliability, stability and power handling capability. The future is cleared for higher power, higher efficiency optical modules thanks to fused silica transmission diffraction gratings.

About the author

Kristian Buchwald is a M.Sc..E.E. from the Technical University of Denmark and Product Manager of gratings at Ibsen Photonics in Copenhagen, Denmark.

Appendix A – Fused silica material properties

For a broad range of demanding applications, fused silica is an ideal material. This section includes selected, important material properties of fused silica

Refractive index

Wavelength (nm)	Refractive index
193	1,56077
248	1,50855
266	1,49968
325	1,48164
351	1,47672
442	1,46622
488	1,46301
532	1,46071
633	1,45702
800	1,45332
1064	1,44963
1550	1,44402

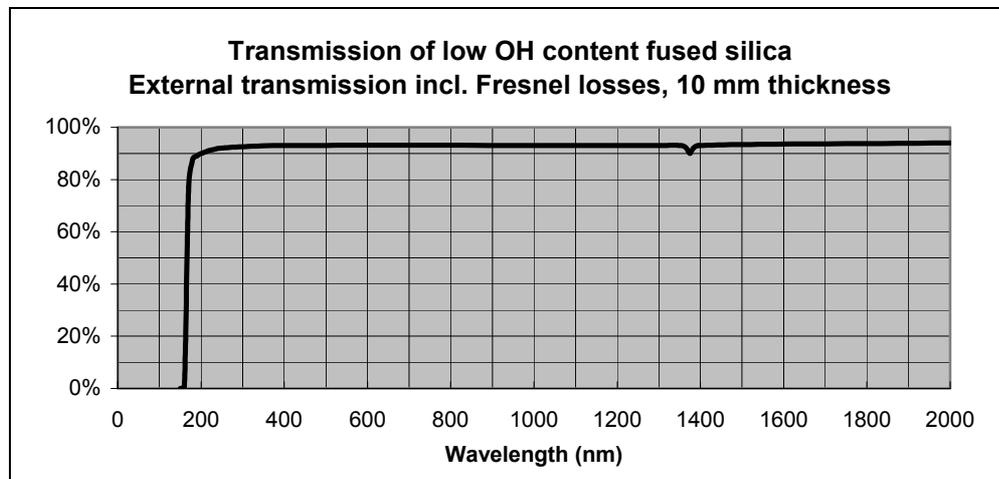
Thermal properties

	Temperature (°C)
Softening temperature	1600
Annealing temperature	1100
Max. working temperature - short term	1200
Max. working temperature - continuous	950

Mean expansion coefficient

$$5.1 \cdot 10^{-7} \text{ K}^{-1} \quad (0-100^\circ\text{C})$$

Transmission spectrum



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