Photonic Submicron-Structures

Effective media for high-performance applications

Progress in the development of lithographic fabrication technologies and their availability for optical applications has moved their use for the realization of novel gratings into the focus of modern optics. Only lithography opens the flexibility to generate almost arbitrary grating patterns and thus make the full potential of grating functions accessible. In particular, the dedicated use of sub-wavelength patterns opens up novel grating functionalities and applications.

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Introduction

Since Joseph von Fraunhofer made the optical grating popular [1] almost 200 years have past and gratings have not lost their attractiveness. Even today, new exciting grating effects are discovered and investigated, and promoted for applications. The huge number of gratings applications stretches from dispersing elements in spectrometers, beam-splitting elements, up to pulse-compression gratings for the manipulation of ultrashort laser pulses. Also, more general structures such as diffractive optical elements (DOE) can be considered as being composed of local linear gratings of varying period and orientation. In this sense, and enabled by improving fabrication technologies, diffraction gratings are going into an increasing number of industrial applications.

When Heinrich Hertz presented in 1888 the first wire grid for electromagnetic waves in the radio-frequency range, Maxwell's equations, as well as the electromagnetic nature of light, were demonstrated by a new type of grating – the zero-order grating or effective-medium grating. Its scaling down from radio-frequency to optical or UV frequencies and its introduction to more general optical applications seems to be a mature topic that has inspired the opticians and challenged the technologists up to now, but will do also in the future. As the desired effective medium optical effect is connected with geometrical feature sizes in the sub-wavelength range the realization of suitable structures is extremely demanding.

The developments in modern lithographic fabrication technologies, especially the advances in resolution and accuracy, paved the way for the use of effective media and their combination with diffraction gratings in real applications. The aim of this paper is to give an insight into this field and demonstrate the possibilities arising from it.

Effective Media Make it Feasible

Diffractive optical elements are often designed for applications that require specifications that seem to be totally unachievable from a fabrication point of view. Such requirements are pushing scientists to follow unusual approaches, and finally it is sometimes astonishing to see such a solution works in reality.

Before we show the potential of sub-wavelength structures in real applications we will briefly discuss the physical principle the effective index medium is based on. For this, we consider a simple linear grating having a period p. By using the grating equation for perpendicular incidence angle

$$\sin \alpha = \frac{m \cdot \lambda}{p}$$

it is possible to calculate the propagation angle α of the diffraction orders of integer index m and for illumination with the wavelength λ. It is obvious that for a decreasing grating period p the number of propagating diffraction orders must also decrease because the given equation does only have a solution if $m \cdot \lambda < p$ holds. As soon as p becomes smaller than the wavelength λ the only solution can be found for $m = 0$. We then speak of a zero-order- or sub-wavelength grating. In this case, the light incident on the grating does not 'resolve' the periodicity of the structure. Instead, it only experiences an effective refractive index averaged from the indices n_s and n_e of the substrate material and the environment (typically air), respectively. The particular effective index is a function of the local fill-factor and typically also depends on the polarization of the light due to the orientation of the grating. In particular, the fill-factor dependency can also be used to realize complex optical functions. This is shown schematically in Figure 1. The left side shows typical structures of a conventional linear blazed grating with a backside antireflection (AR) coating and a pixelated computer-generated hologram (CGH). The realization of both three-dimensional surface profiles is not really a straightforward process. Lithographic techniques such as laser- or electron-beam writing can be used but these methods work best for the generation of binary patterns only. Multilevel approximations of continuous surface profiles can be achieved by multiple binary patterning steps [2]. However, if the alignment of the different lithography steps with respect to each other is not perfect the resulting structure can exhibit a considerable amount of stray light, the diffraction efficiency is reduced, and also the quality of the transmitted wave-front might be badly affected.

The way out of this dilemma is the use of an effective refractive index structure with a locally varying fill-factor for the realization of the required continuous-phase function based on the approach described above. The effective index equivalent to the three-dimensional surface structure is sketched on the right side of Figure 1. Also, the AR layer on the backside of the blazed grating can be replaced by a sub-wavelength grating with a vertical variation of the fill-factor.

It becomes clear that the local fill-factor of the binary effective index structure somehow corresponds to the phase delay introduced by the conventional 3D surface profile. However, the exact relation between the phase delay and fill-factor is far from linear and must be optimized for a particular element by detailed calculation.

This method of realizing highly efficient DOE by an effective index structure was experimentally demonstrated some time ago [3]. From an application point of view the important advantage of this approach is the one-step lithographic fabrication of the structure. There is no need for multiple and precisely aligned lithography steps, as would be required for the fabrication of multilevel profiles or the accurate control of the resist gradation curve in using analog lithography [4].

In the following, some prominent examples will demonstrate the advantage that can be taken by implementing effective media instead of conventional solutions.

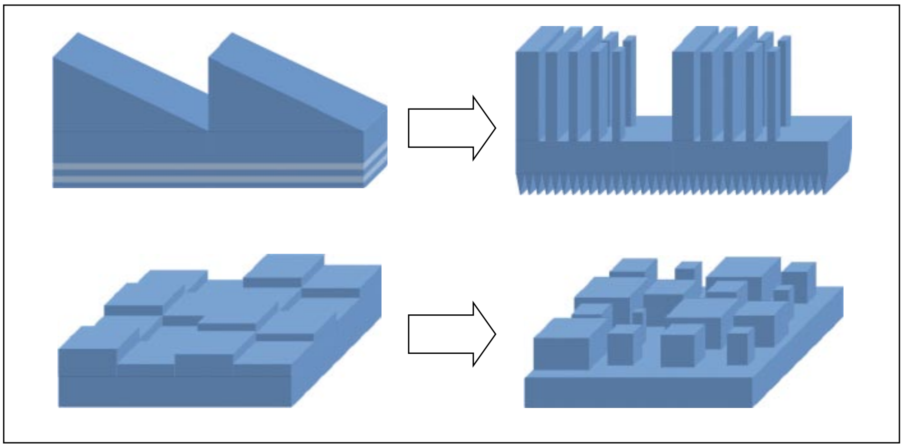

FIGURE 1: **Conventional solution (left) and its replacement by an effective media approach (right) for the spectrometer grating (top) and for the scatter plate (bottom).**

The GAIA-Spectrometer Grating

Spectrometer gratings are the heart of some optical instruments for different earth-observation and scientific space missions. As satellite instruments typically operate close to the technologically accessible limits the realization of the respective gratings is also extremely demanding. Critical parameters are the diffraction efficiency and its polarization dependency, the wave-front error introduced by the grating, stray-light performance, and usability in a space environment. An example of such an element is the grating for the radial velocity spectrometer of the astrometry mission GAIA of the European Space Agency (ESA). This spectrometer is dedicated to the measurement of the star distance for objects located in our home galaxy down to a relative brightness of m = 18 light magnitude. The distance measurement is based on a characterization of the red shift of a calcium triple spectral line group in the wavelength range λ = 847–874 nm. In order to achieve the desired sensitivity the grating having a period of

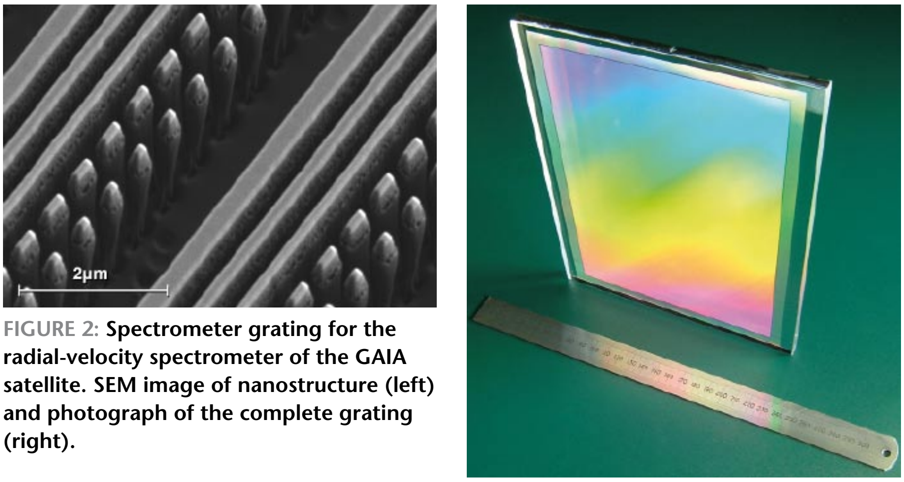

FIGURE 2: **Spectrometer grating for the radial-velocity spectrometer of the GAIA satellite. SEM image of nanostructure (left) and photograph of the complete grating (right).**

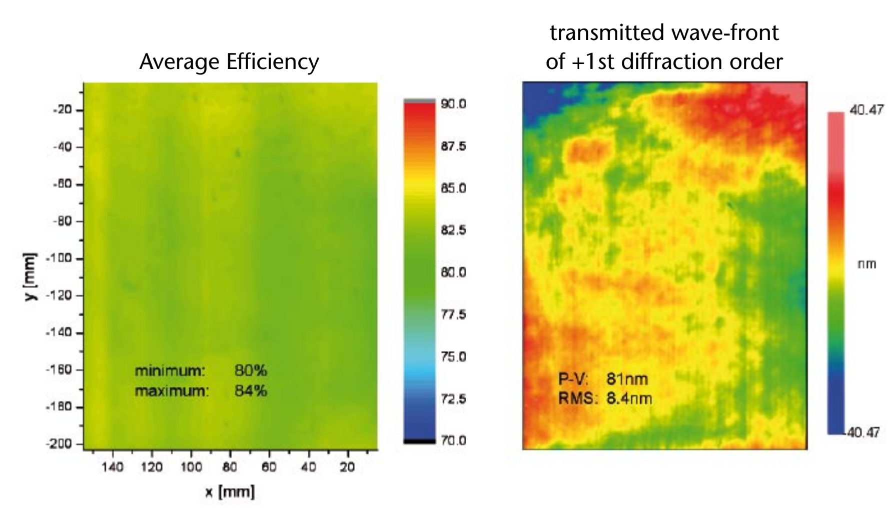

FIGURE 3: **Diffraction efficiency (unpolarized light) and transmitted wave-front error measured on the flight model of the GAIA-grating.**

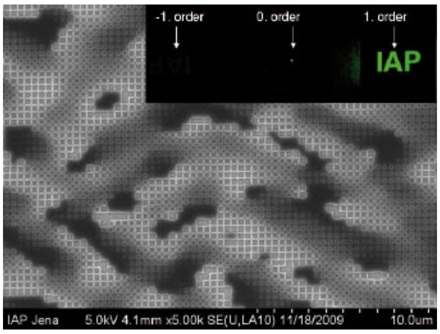

FIGURE 4: **SEM image of a diffusor structure realized by an effective-index approach. The inset shows an optical measurement of the far-field image generated by the element.**

p = 3.15 µm needs to have a large size of 155 mm × 205 mm, its wave-front error is limited to a maximum of 5 nm (rms) within a sub-pupil of 50 mm × 42 mm, and the diffraction efficiency for an almost perpendicular incidence angle has to exceed 70%.

While each of these parameters alone can be achieved with gratings realized by any standard technology their simultaneous implementation is a perfect application for an effective-medium structure as shown in the upper part of Figure 1. However, in order to keep the realization within the technological constraints a detailed optimization of the grating substructure is necessary. As the polarization sensitivity of the diffraction efficiency is also of concern we finally decided to compose the effective-medium pattern of a combination of 1D bars and 2D pillars. Only by this approach was it possible to keep the smallest lateral feature size above 200 nm. Together with the required structure depth of h = 1.8 µm this restricted the aspect ratio of the pattern to 9.

The final design led to a maximum diffraction efficiency of approximately 85% for both polarization directions. We fabricated the grating by electron-beam lithography and reactive ion etching on a fused silica substrate. Figure 2 shows a photograph of the full-size grating together with a SEM image of the effective medium substructure. The pillar structure has a periodicity in the y-direction of p_y = 600 nm and is thus also a sub-wavelength pattern not leading to additional diffraction orders in this direction.

A mapping of the polarization-independent diffraction efficiency measured on the flight model of the grating together with an interferogram of the transmitted wave-front error in the +1st diffraction order is shown in Figure 3. The average of the diffraction efficiency exceeds 80% with a maximum polarization sensitivity of 5.4%. The sub-pupil wave-front error is within the specification of < 5 nm (rms) on 80% of the grating area. Just in one corner of the grating this value is exceeded by 2.7 nm.

Extended Scatter Plate

The approach of realizing a locally varying phase function is not only restricted to gratings but can also be used to ease the fabrication of multi-level diffractive elements. One example is a diffusor plate having a deterministic scatter property like a picture or a scatter function for an eye-box used in a display. As the desired optical function is not symmetric to the optical axis a phase function is required which consists of multiple phase values. The typical realization approach would be the use of binary-optics technology for implementing the phase function by a multi-level height function. The use of effective media offers a way to realize the structures with a single lithography step only, and thus to overcome the mentioned difficulties. Again, the local phase function can be implemented by a binary structure with a 2D variation of the fill-factor as sketched in Figure 1. Figure 4 shows an example of an off-axis diffuser structure realized by this approach. As an additional advantage an almost arbitrary number of phase levels can be generated by small steps in the variation of the area fill-factor.

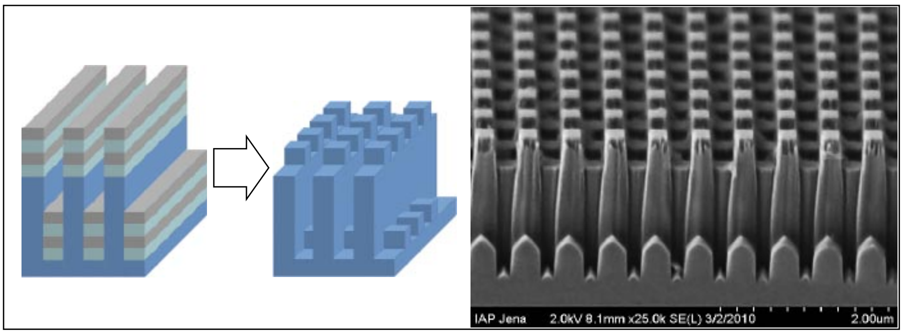

FIGURE 5: **Principle of replacing an antireflection layer on top of a grating by a sub-wavelength pattern (left) and example of a pulse compression grating with AR-structure on top (right).**

Pulse Compression Grating

The diffraction efficiency of transmission gratings is limited by the Fresnel reflection of its surface. In particular, pulse-compression gratings that use strong oblique incidence and small periods in order to get high dispersion suffer from this problem. Depending on the period and the angle of incidence reflection losses can grow up to 20%. As already mentioned in the introduction, effective media based on sub-wavelength gratings can also be used for reducing reflection losses of optical surfaces. We have used this principle to reduce the reflection losses of the high aspect ratio transmission gratings applied for laser-pulse

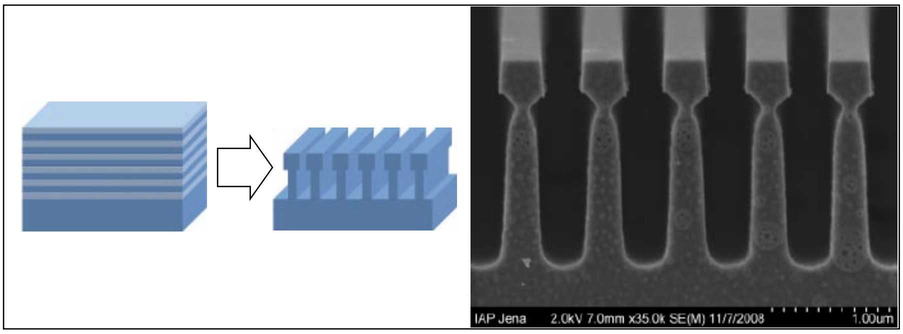

FIGURE 6: **A conventional high reflective dielectric layer stack can be replaced by a special monolithic grating.**

compression. Figure 5 shows a sketch of the grating profile and the fabricated pulse-compression grating equipped with the antireflective sub-wavelength grating. Due to the fabrication technology the upper grating profile has a binary shape, while the lower one has a triangular-shaped top. Theoretical calculations show that such a grating is theoretically able to suppress the reflection losses completely. By utilizing this grating architecture we experimentally achieved diffraction efficiencies of >97% instead of the theoretical limit of 92% without the antireflective grating. This is a reduction of the reflection loss of at least 5%.

Monolithic Dielectric Mirror

Commercially available highly-reflective dielectric mirrors are commonly built of multilayer coatings containing at least two different layer materials. Due to the complex alternating coating technique, a critical laser-induced damage threshold, and most severely a remarkable internal thermal noise level, these dielectric stacks appear as a drawback for special applications such as in the field of optical ultrahigh precision measurements.

Alternative mirror setups with a considerably reduced coating thickness are known as guided-mode resonant waveguide gratings. By utilizing the resonant behavior of light coupled by a sub-wavelength periodic structure into a high refractive index layer attached to a low refractive index substrate a high reflectivity can be achieved. However, besides the nanopatterning of the grating at least one residual coating step is involved in the fabrication of such elements.

By introducing an effective media low-index layer instead of a homogeneous one, earlier grating configurations can be advanced to purely monolithic mirror architectures [5]. Without the need for adding any other material to the mirror substrate, this new approach might give a promising solution for long-standing problems, as mentioned above. A suitable monolithic sub-wavelength structure having a T-shaped grating profile is sketched in Fig. 6. If it meets particular design dimensions for a given wavelength this structure provides perfect reflectivity in theory. Here, the upper grating region with its high fill-factor enables the resonant excitation of higher diffraction orders, while the lower grating only allows the fundamental order to propagate. Thus, the upper grating region acts similar to a waveguide that is separated from the substrate by the lower fill-factor region. Similar to a conventional homogeneous layer, the remaining fundamental mode can show complete destructive interference for all light transmitted through the substrate.

For a processed silicon substrate, an outstanding value of resonant reflection of > 99.8% for a wavelength of 1550 nm under normal incidence was experimentally observed. This is in full agreement with a rigorous model [5]. We expect that indeed considerable improvements towards a perfect reflectivity are possible with improved electron beam lithography and etching technologies.

Conclusion

Almost 20 years after the first experimental realization of optical functions based on effective refractive index structures this approach is finding its way into real-world applications thanks to the capabilities of modern lithographic fabrication technologies. We have shown a selection of applications that clearly benefit from the effective index principle. In some cases, e.g. in high-performance space applications, there is sometimes no alternative to the use of such sub-wavelength-structured elements.

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The Fraunhofer IOF was founded in 1992 and has approximately 140 employees. The Fraunhofer IOF is a competent partner to industry and is also a supplier to the public sector. Research and development at Fraunhofer IOF focuses on optical systems technology with a view to continually improving the control of light from generation via guiding and manipulation up to its application. The core competences include optomechanical design and simulation, multifunctional optical coatings, manufacturing and integration techniques of optical components and systems, optomechanical precision systems, measurement systems and sensors. The Fraunhofer IOF escorts their clients all the way from the idea to prototype.

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