Diffractive Optics in Industry and Research – Novel Components for Optical Security Systems

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ABSTRACT

Design and manufacturing of diffractive optical elements (DOEs) are presented. Mass replication methods for DOEs are explained including UV-replication, micro-injection moulding and reel-to-reel production. Novel applications of diffractive optics including spectroscopic surface relief gratings, antireflection surfaces, infrared light rejection gratings, and light incoupling into thin waveguides are presented.

Keywords: diffractive optics, diffraction, electron beam lithography, grating, spectroscopy, antireflection

1. INTRODUCTION

Diffraction is considered typically as a restriction in many optical systems. However, with the science of diffractive optics, one takes the advantage of the diffraction by applying a micro- and nanostructured media to interact with the incoming light field[1]. This pre-modelled diffraction can produce many optical field that are (almost) impossible to generate with the conventional study of the refractive optics (that uses Snell's law at the boundary of two materials). It is realistic to assume that when one uses diffractive structures with feature sizes of the wavelength, we can pack several optical functions to a small size. This is particularly true in most diffractive optical application.

Typically the advantages of diffractive optics are small size, lower cost of a complicated optical systems, lower weight, new optical functions beyond classical optics, and diffractive gratings also can be applied to system integration. Even the advantages are great, diffractive optics has also its restrictions: gratings are typically wavelength dependent, and can only provide limited diffraction efficiency to the designed optical field. These drawbacks are typically supplemented with good optical design, compact size and the cheapness of the optical system.

In this article, we go briefly through the design of diffractive optics. Designing of diffractive optics is important since only a well-designed diffractive grating can provide the best possible result after the master manufacturing and the mass replication. The design of diffractive optical elements (DOEs) is briefly introduced with approximate and rigorous methods.

The manufacturing of DOEs is described. The process includes resist processing, exposure (electron beam lithography, direct laser writing, or holographic recording), development and nickel tooling. In addition, highly periodic linear and crossed diffraction gratings can be produced with interference lithography and will be described in details.

It is worth noting that the first single master of diffractive optical elements is quite expensive. However, the most of the gratings can be mass replicated, which leads to a relatively cheap copy of the diffractive pattern and therefore makes it

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possible to use diffractive elements in real commercial products. The replication methods include reel-to-reel embossing, micro-injection moulding and UV-replication.

The major aim of the article is to illustrate several commercial and scientific applications of diffractive optics. These include spectroscopic gratings, antireflective surfaces, inductive grids for infrared rejection (while transmitting visible light), light incoupling into thin waveguides with radial gratings, and additive colour mixing with diffraction gratings.

2. DESIGN OF DIFFRACTIVE OPTICS

The design of the diffractive optical elements can typically be divided into two subdomains according to the analysis methods involved. The first and the simplest is the scalar domain[2], where we assume that the signal is paraxial and the diffraction angles are relatively small (<5 degrees). In this case, the famous thin element approximation and the Fast Fourier Transform (FFT) can be applied to optimize the signal[2]. Typical examples on such elements are diffractive beam shaping and splitting elements designed with Iterative Fourier Transform Alghorithm (IFTA) and "Blazed" type gratings with a relatively large grating periods.

If the grating period is near the illumination wavelength, we enter the resonance domain of diffractive optics. Now the scalar design methods are not valid anymore and rigorous diffraction theories must be utilized. Usually we resort to well known methods such as Fourier Modal Method (FMM)[2] and Chandezon's method (C-method)[3,4]. Softwares using rigorous design methods are now even commercially available even though in several cases more esoteric approaches must be used. Rigorous methods calculate numerically the diffraction efficiencies (and complex amplitudes of the fields) when a grating structure is given as an input. Linear grating problems are solved with 2D geometry and the numerical calculation is fast even with large grating periods. However, in the case of 3D grating geometries (for example crossed grating) the computational costs can be enormous.

3. MASTER MANUFACTURING

Direct electron- and laser beam writing are the most efficient methods to manufacture different *modulated* grating structures. With electron beam lithography the resolution of ~40 nm and with laser beam writing the resolution of ~0.8 μm can be reached. The direct beam writing can be divided into two main categories: the fabrication of binary grating is illustrated in Fig. 1 (a) and the case of continuous gratings is illustrated in Fig 1 (b). With binary type gratings the high contrast resists are used to obtain very high resolution and vertical sidewalls for the diffraction gratings. However, the highest diffraction efficiency is not reached with asymmetric signals since light is diffracted symmetrically into two directions (true at least at the zero incidence angle of the illuminating beam). This means that at least 50% of the power is lost (if the signal in the signal window is not symmetrical). To avoid this problem, continuous (asymmetrical gratings) are widely used to steer the light in one specific direction. These gratings can be manufactured by a variable-dose direct patterning of the analogue resist layer[5]. Nevertheless, inclined side-walls are typical problems arising from the fabrication of continuous structures. This problem appears with low voltage electron beam lithography owing to the electron beam scattering at the resist layer with thick resists (~1-5 um), but can be avoided with direct laser patterning. Furthermore, with laser lithography the resist layers up to 100 μm can be exposed depending of the absorption curve of the corresponding resist.

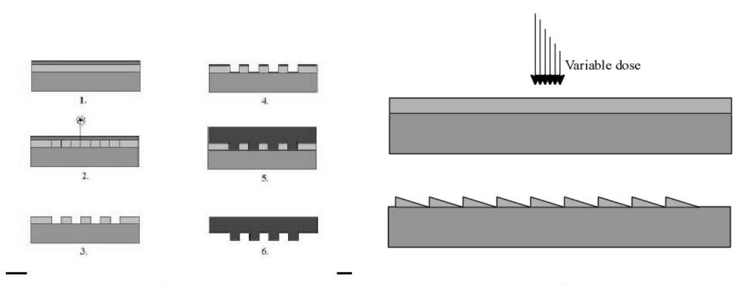


Figure 1: a) Binary grating manufacturing: 1. Resist spinning on the substrate, 2. direct electron beam, laser writing, or holographic recording, 3. development, 4. evaporation of conductive layer, 5. nickel electrolysis, and 6. nickel separation (1st generation shim). b) principle of direct writing of continuous grating with a variable dose to analoque resist (phases 2 and 3 are shown).

Holographic lithography (Figure 2) is an efficient way to produce large-area highly periodic grating structures. Even though the principle of the holographic interference lithography is simple, a lot of practice is needed to achieve intact and error free grating structures with defined grating fill factor. Typically this method is used for linear gratings and crossed gratings manufacturing over a large area (up to >50 cm x 50 cm).

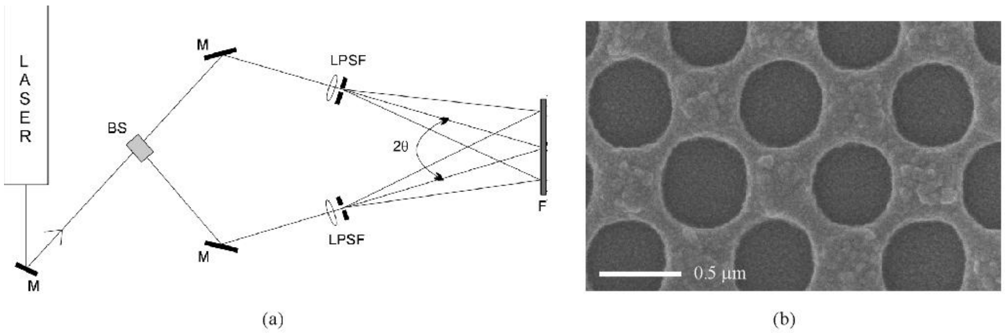


Figure 2: a) Principle of interference lithography. Laser beam is divided into two beams (with beamsplitter BS) and the coherent beams are directed with mirrors (M) to the resist coated sample plate (F). The exposed grating period is defined with the light angles of $d=\lambda/2\sin\theta$, where λ is the exposure wavelength. b) Manufactured crossed grating in negative resist (exposed with λ=364 nm), grating period is ~500 nm and the resist depth is ~200 nm.

After the resist exposure, the Nickel tool is grown with galvanic process (Figure 1). This process is widely used in many field of CD and DWD manufacturing and is widespread in nanoimprint lithographic processes. The nickel tool can be created as a positive-negative-positive series and therefore from one 1st generation nickel shim one can produce ~100 nickel shims. It is worth stressing that also large area nickel shims can be produced and those are mainly used in reel-to-reel embossing process to manufacture different types of holograms and diffraction gratings. A large area Nickel tool is seen in Fig. 4 (a) where it is wrapped around a heated cylinder.

4. MASS REPLICATION

UV- replication is a method that can be used in a precise replication of the manufactured master. The process is simple. We put a drop of UV curable material on the top of the grating master (Nickel or SiO2), cure it with UV- light and for the separation just peel off the manufactured replica. However, some practice is needed to manufacture not only air bubble free but also optically flat surfaces (imaging optics quality), and to save the master. The master is typically anti-adhesion treated so that the UV curable material will not stick to the master. With a good anti-adhesion treatment the master can endure several tens of thousands of UV-replication steps. In Fig. 3 we present some results of the UV-replicated diffraction gratings that are used in spectroscopic applications and diffractive Bragg imaging lenses[6]. High precision replicas are needed also for imaging optical applications.

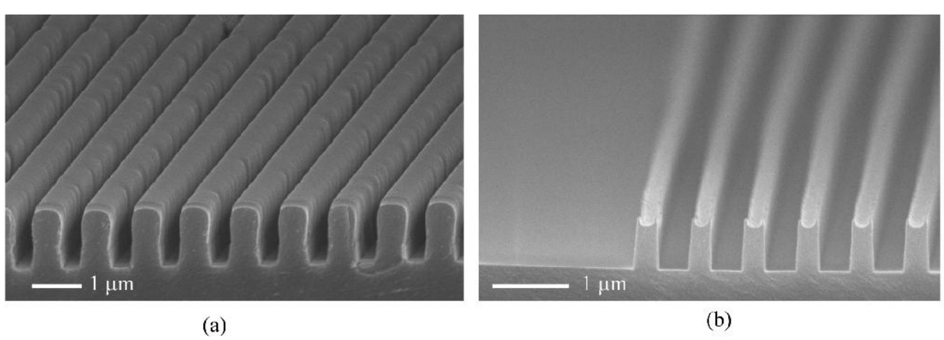


Figure 3: a) UV cured linear binary grating with a feature size of 0.5 µm for spectroscopic applications and b) UV cured “Bragg” imaging diffractive lens structure.

Injection molding is a widely used method in consumer plastic manufacturing. CD and DVD discs are the products found in everybody's home. The discs contain nanostructures with features less than 1 μm. However, in diffractive optics production these feature sizes can provide only limited diffraction efficiency and therefore it is essential to improve the injection molding capability. We have developed micro-injection molding process for several years to achieve good quality nanostructures on different plastics. The injection molding process has been optimized for DOE production and in Fig. 4 we present some results achieved. The material here is polycarbonate (PC) and the grating features ~200 nm are well replicated.

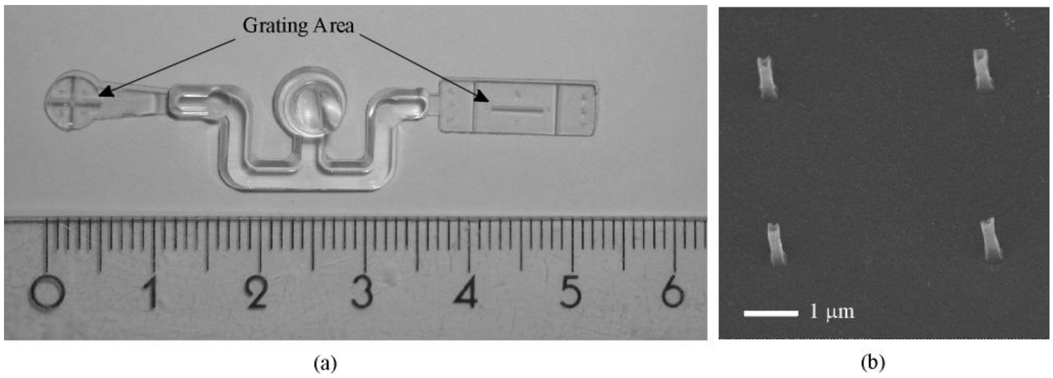


Figure 4: a) Micro injection molded plastic piece (centimeter unit is seen). b) Micro-injection molding resolution test with a feature size of <300 nm and with a depth >300 nm.

Reel- to-reel production (Figure 5) is the fastest method to manufacture DOEs at high speed. In this case the Nickel tool is wrapped around a heated cylinder. By running a plastic foil through the calendar the gratings on the Nickel tool are replicated on the foil (thickness between 20-500 μm). The most important aspect of this method is that it yields equal quality DOEs as the end product. This makes it attractive for many applications where serie-to-serie repeatability and the cost are important. It is worth noting that with the system shown in Fig 5, around 1 million pieces of 3 x 4 cm sized diffractive optical elements can be achieved within a working day (with the web speed of 15 meters/minute).

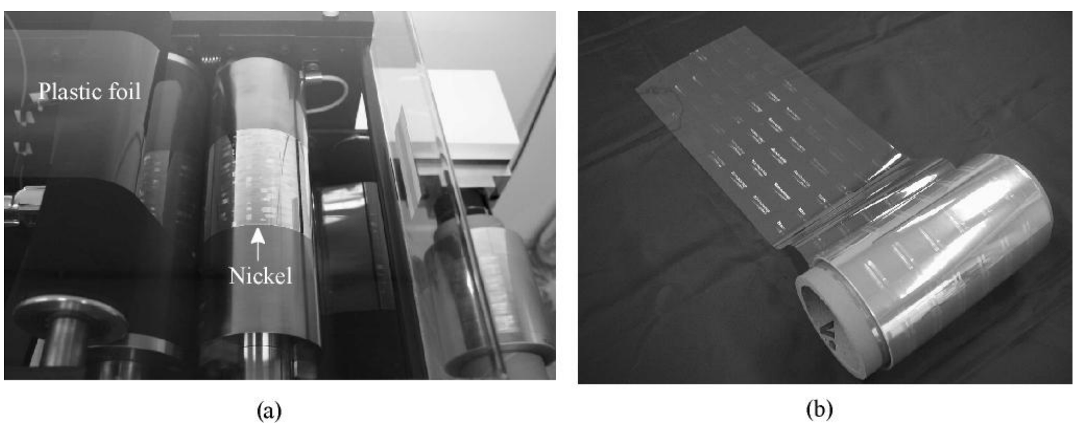
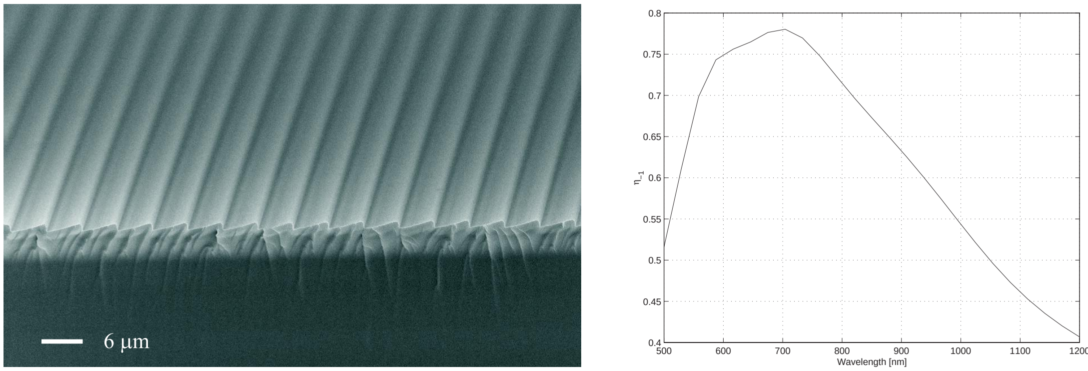


Figure 5: a) Reel-to-Reel production of diffractive optics. Nickel tool is wrapped around the cylinder that is heated and pressed against the plastic foil. b) (Small) roll of the material embossed with R2R production.

5. NOVEL APPLICATIONS OF DIFFRACTIVE OPTICS

5.1 Spectroscopic gratings

One of the first applications of diffraction gratings are spectroscopic gratings dividing the illuminating light into a spectrum and used in spectrometers[7]. With binary gratings only a limited diffraction efficiency can be achieved. This problem can be overcome with the use of asymmetric blazed type gratings. We used rigorous diffraction theory to optimize the diffraction properties. In Fig 6 a) is presented the optimized grating structure (written with direct write laser lithography) and in Fig. 6 b) the corresponding for the wavelength range of 500 nm-1200 nm. Highest diffraction efficiency >77% can be reached.

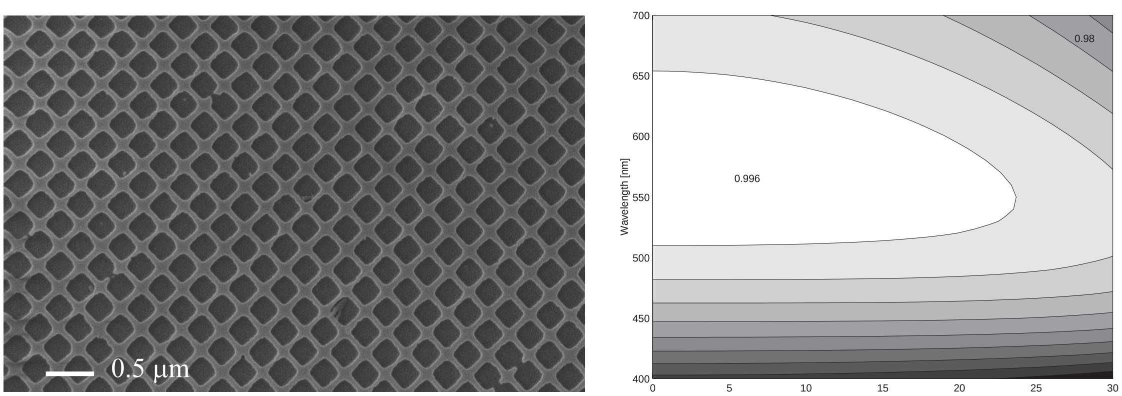


(a) (b)

Figure 6: a) Blazed grating structure, grating period 6 µm, grating depth 1.1 µm and refractive index n=1.54 b) Theoretical diffraction efficiency as a function of wavelength.

5.2 Antireflective gratings

Antireflection property is important in almost every optical system. For example, a single camera objective can lose ~50% of the light without an antireflection thin film on the top of the lenses (a single MgF2 antireflective film can provide <1.5% reflection from one boundary). However, this cannot handle all the large visible spectrum of light. A diffractive solution for antireflection is to use crossed gratings as illustrated in Fig. 7 a). The grating can be manufactured to different plastics. The local grating period is 300 nm (smaller than the smallest wavelength), the grating fill-factor is 50% and the depth of the grating 130 nm. This grating works well for the visible spectrum and also for an oblique angle of incidence as seen in Fig 7 b). The minimum transmission is 97.8 % and the maximum transmission obtained from one boundary is 99.6%, that value is superior to the typical antireflective MfF_2 thin film. Slightly better results can be obtained by making the grating more triangular shape or manufacturing a "moth-eye" structure with holographic recording.

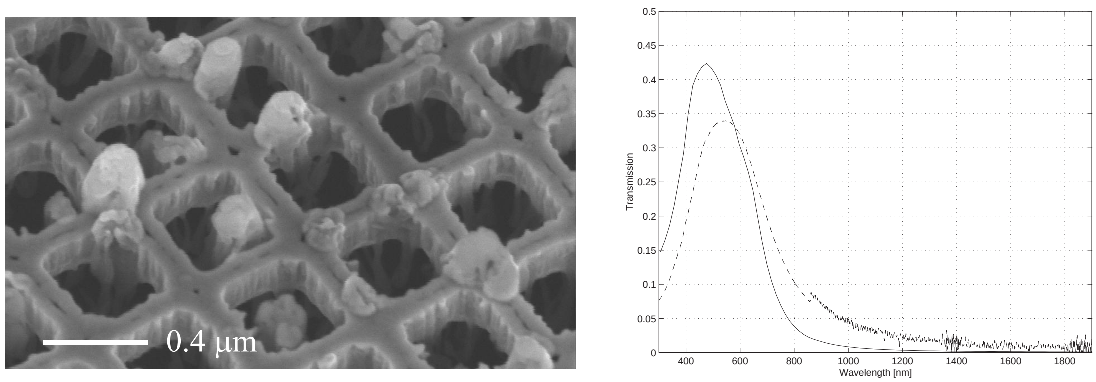


(a) (b)

Figure 7: a) Antireflective binary crossed grating is SiO2 b) theoretical transmission as a function of wavelength and the incidence angle.

5.3 Inductive grids for infrared rejection

Second grid type application is a crossed grating for rejecting the transmission of infrared light[8,9]. This grating works similarly to the metal grid on the microwave oven, now the wavelength is just much smaller (as well as the grid period). During the research we have found out that the best material for this applications are Nickel and Gold due their better productivity. In Fig. 8 a) is shown the crossed grating manufactured with low-energy electron beam lithography, overgrowing (ALD) and etching techniques to Iridium material. The grating depth is 400 nm and the transmission spectrum is shown in Fig. 8 b). Even the correspondence between experimental and theoretical results is not perfect yet, it presents relatively good suppression of the infrared light.

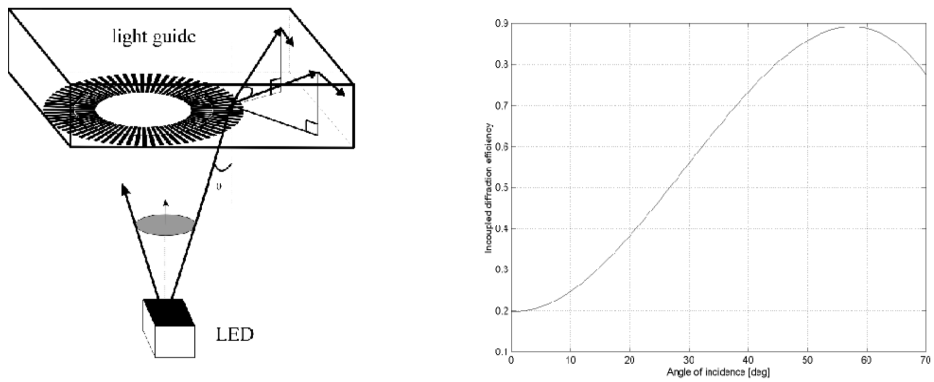


(a) (b)

Figure 8: a) Iridium grid grating for infrared rejection b) experimental (dashed line) and theoretical (solid line) transmission of such a grating as a function of wavelength.

5.4 Light coupling on thin waveguides with diffraction gratings

Light incoupling to thin waveguides is particularly important for mobile applications where LED light is used as a light source[10]. However, the light coupling problems are obvious. A diverging LED light must be coupled into thin waveguide with high diffraction efficiency. Furthermore, a good light incoupler is also a good light outcoupler and therefore it is important to prevent the incoupled light from hitting back to the grating structure. This leads to a relatively thick waveguide that in most cases cannot be accepted. Radial light incoupler solves the above mentioned problems[11]. After the design we found out that the binary diffraction gratings with pure conical incidence angle provides an efficient light incoupling with a diverging monochromatic LED light. In Fig. 9 a) is shown a picture of the light incoupling geometry and in Fig 8 b) is shown the theoretical diffraction efficiency as a function of the incident angle θ (grating periods $d<\lambda/\cos(\theta)$). The total incoupled light efficiency is ~70% for a monochromatic wavelength of λ=575 nm. We manufactured the grating system and injection moulded the whole mobile phone keypad lightning system with 8 incoupler gratings. The main result of the research was that we were able to reduce the waveguide thickness from 1.2 mm to 0.6 mm still maintaining the incoupled light efficiency when compared with refractive solutions. The result is superior since the system can be injection moulded in mass series. The system can be efficiently used in keypad lightning, and diffractive light diffusers. Light incoupling will be expanded to the white LED light illumination in the near future.



(a) (b)

Figure 9: a) Light incoupling geometry with radial light coupler, b) theoretical diffraction efficiency of the grating as a function of angle of incidence.

6. CONCLUSIONS

We have described the design, mastering and mass manufacturing methods of diffractive optics. Diffractive optics produces several novel optical applications with relatively cheap price with mass manufacturing processes.

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