Optimization and manufacturing of gold gratings for pulse compression

Felix Koch*, Oliver Schönbrodt*, Matthias Burkhardt*, Dennis Lehr*, Tilman Glaser*, Stefan Sinzinger**

*Carl Zeiss Jena GmbH, Jena
**Technische Universität Ilmenau, Ilmenau

mailto:felix.koch@zeiss.com

To achieve decent diffraction efficiencies with gold-coated gratings, e.g. for pulse compression, the profile shape has to be optimized based on the manufacturing process. In our contribution, we report on the design and holographic manufacturing of Au-gratings with up to 94 % diffraction efficiency at 1050 nm central wavelength.

1 Introduction

There are several applications for diffraction gratings in laser physics and -engineering, e.g. as filters for bandwidth-narrowing and wavelength-tuning or for spectral beam combining and temporal pulse shaping in ultrafast lasers. Gold-coated diffraction gratings are still popular for laser pulse compression due to their rather simple and low-cost fabrication, especially compared to more sophisticated structured dielectric multilayers or dielectric transmission gratings [1]. To achieve high diffraction efficiencies (>90 %) with a practically feasible design, it is beneficial to consider the manufacturing process already in the design stage. In our contribution, we demonstrate a holistic design approach for holographically recorded gratings optimized for laser pulse compression in the NIR range as well as first experimental results from the manufacturing of these gratings yielding close to theoretical performance.

2 Design approach

The direction of the diffraction orders for one-dimensional gratings with in-plane incidence is completely described by the grating equation that arises from the interference of the light periodically scattered from the grating grooves:

$$\sin\theta_m = \sin\theta_i + m\lambda/\Lambda, \qquad (1)$$

where θ_i and θ_m are the incidence and diffracted angle for order *m* respectively, λ is the wavelength and Λ the period. To achieve the desired high angular dispersion, the gratings utilized for laser pulse compression typically work in the resonance domain with only one propagating diffraction order besides the 0^{th} order. Hence, neglecting scattering and absorption, also the energy can only be distributed between these two orders and high efficiencies can be achieved by controlling the profile shape [2]. In this highly dispersive regime, the polarization and the field propagation inside the grooves cannot be neglected, and hence, to correctly model the grating, rigorous numerical methods have to be applied, i.e. directly solving Maxwell's equations without further physical approximations. For our contribution, we applied the rigorous boundary integral equation solver *PCGrate*, that has particularly proven well-suited for metal-coated gratings with high refractive index contrasts and continuous profiles. The mathematical details of this method are beyond the scope of this paper, the reader is referred to [3]. To incorporate the manufacturing process, the Maxwell solver was combined with a self-written semi-empirical simulation of the photoresist development based on the string method [4]. In Fig. 1, the formation of a symmetric grating profile inside the photoresist during the development process is demonstrated. The false colors in (a) correspond to the local development rate [nm/s]. Exposure of AZ1505 positive resist with 250 mJ/cm² dose from each arm and a contrast of 0.8 was assumed. The model is based on the experimentally determined resist characteristic depicted in (b).

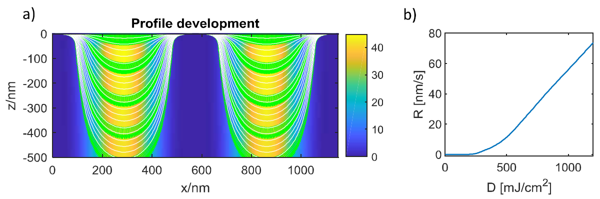

Fig. 1 *Semi-empirical resist simulation. (a) Intermediate steps for symmetrical grating, (b) experimental resist response for 460 nm and diluted AZ303 developer.*

Although, the complex resist chemistry is neglected, our semi-empirical model was found to exhibit good correspondence to experimental profiles.

Furthermore, to efficiently address the parameter space of the resist model, a multi-parameter optimization based on the Interior Point method was incorporated into the design routine. The former is a deterministic local gradient-based optimizer. A merit function based on the RMS-deviation from 100 % - 1^{st} reflected order efficiency for TM polarization was minimized for 1740 L/mm, 72° angle of incidence (10° deviation from the diffracted order at 1054 nm) and a wavelength range from 1040 to 1070 nm in steps of 5 nm. The parameters were modulation dose, offset dose, development time and resist thickness and have been restricted to reasonable bounds. A statistic multi-start approach with 100 start points was used to avoid poor local minima. More details on the optimization method and merit function are given in [5] and the references therein, where a similar optimization routine is described for dielectric gratings.

3 Results and manufacturing

The resulting target profiles were expectably sine-like with a depth of about 140 nm and a duty cycle of 0.46. For manufacturing, 90x90 mm² fused silica substrates were spincoated with 140 nm of AZ1505 positive resist and exposed to the interference pattern of two filtered and collimated waves [6]. The parameters from the resist optimization were adapted and slightly refined based on AFM measurements to resemble the target profiles as closely as possible. After mastering, the grating was, without etching, directly replicated to an even generation (for best profile conservation) using an epoxy-resin-based in-house process and coated with approx. 100 nm gold using thermal evaporation. In Fig. 2, the elementary cells of one master (S1) and one replica grating (S1-rep.) are compared to the target profile from the optimization and show good correspondence.

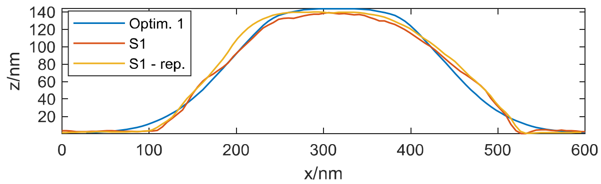

Fig. 2 *Target profile from resist optimization compared to experimental AFM elementary cells from one master and one replica grating.*

Spatially resolved diffraction efficiency measurements were carried out using a tunable diode laser and an automated *x-y*-stage. Due to the measurement setup, the incidence angle was 60.3°. Figure 3 shows the spectral efficiency compared to simulations based on the target and measured profiles as well as a homogeneity measurement at 1045 nm. A maximum TM efficiency of 93.3 % was attained, which is close to the optimum curve. For smaller deviations from Littrow incidence, simulations with the real profile yield even higher values of up to 96 %.

4 Conclusion

We described an integrated design approach for holographic diffraction gratings recorded in positive photoresist. A semi-empirical photoresist model was combined with a rigorous boundary integral equation solver and a multi-start Interior Point optimizer to find both, performant and experimentally

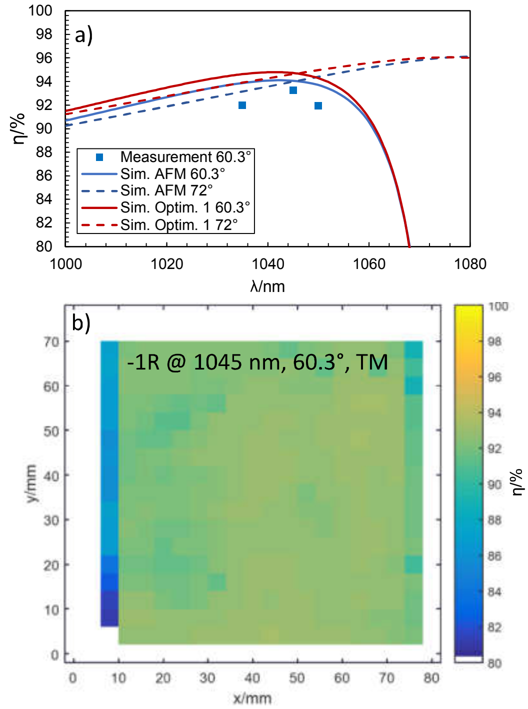

Fig. 3 *Diffraction efficiency measurements vs. simulation. (a) Spectral dependence for center position compared to simulations based on the corresponding AFM profile and the target profile. (b) Spatially resolved efficiency measurement.*

feasible solutions for a given diffraction efficiency requirement. Reflective gold-coated gratings for laser pulse compression were manufactured using interference lithography and subsequent replication. Diffraction efficiencies of >93 % at 1045 nm were achieved and agree well with the theoretical design. The described approach can help tailoring diffraction efficiencies for various applications.

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DGaO-Proceedings 2018 – *http://www.dgao-proceedings.de* – ISSN: 1614-8436 – urn:nbn:de:0287-2018-A027-3

submitted: 19.Jul.2018 published: 20.Jul.2018