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Research paper

Manufacturing of highly-dispersive, high-efficiency transmission gratings by laser interference lithography and dry etching

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ABSTRACT

Diffraction efficiency for transmission gratings with period-to-wavelength ratios smaller than 0.6 e.g. for laser pulse compression is mainly limited due to reflection losses from imperfect effective refractive index matching. In our contribution, different approaches for achieving high efficiencies by reducing these losses are discussed based on 1d and 2d rigorous coupled wave analysis. These include multilayers underneath the corrugation, sub-wavelength gratings and optimized non-binary profiles. Experimental results from the manufacturing of 1700 l/mm gratings for 1030 nm center wavelength using two-beam interference lithography and reactive ion beam etching are presented. Diffraction efficiencies of above 96% were achieved, significantly exceeding the theoretical limit for widely used monolithic binary profiles in this application.

1. Introduction

In the last decade, short pulse lasers with growing peak powers and pulse energies increasingly gained in significance, not only for fundamental research, but also for industrial applications like in medical technology and material processing [1]. The technique of chirped pulse amplification (CPA) can enormously boost the manageable pulse energies [2]. As the dispersive elements for CPA, transmission gratings are particularly popular for industrial applications because they can be utilized in the advantageous Littrow-configuration. Moreover, compact compressor setups using only one transmission grating are simple to realize and the use of dielectric materials allows for high efficiencies and Laser Induced Damage Thresholds, without the need for complex multilayer designs [3–6]. The drawbacks, however, are due to non-linear self-phase-modulation and self-focusing effects in the volume material [7]. Diffraction efficiency for surface transmission gratings with period-to-wavelength ratios smaller than 0.6, popular for their high angular dispersion, is mainly limited due to reflection losses from imperfect effective refractive index matching [8]. Amongst the available micro- and nanopatterning technologies, laser interference lithography (LIL) is an adaptable, cost effective and maskless option that is particularly well-suited for periodic structures with a wide range of attainable profiles [9]. In this contribution, different approaches for obtaining high diffraction efficiencies for highly dispersive gratings are discussed. Experimental results from the manufacturing of 1700 l/mm fused silica gratings for 1030 nm center wavelength using two-beam laser interference lithography and reactive ion beam etching (RIBE) are presented.

2. Design approaches

For pulse compression gratings, but also for further laser applications like spectral beam combining in laser diode arrays [10], besides diffraction efficiencies close to unity, also high angular dispersions are required to achieve the necessary performance with compact setups for the given application. The wave vectors (i.e. directions) and dispersion characteristics of the propagating transmitted and reflected diffraction orders are governed by the grating eq. [11]. The smaller the period-to-wavelength ratio, the higher the dispersion. It is moreover well-known that for the first order Littrow (or “Bragg”) incidence where the -1st reflected order is diffracted back into the incidence direction and -1st and 0th transmitted order propagate symmetrically with respect to the grating normal, diffraction efficiencies close to 100% can be achieved with symmetric profiles etched into dielectric materials at least for one polarization [12]. However, this also imposes the necessary condition that only the 0th and -1st order propagate and thus transport energy, which from the grating eq. (for Littrow incidence) can be expressed as

$$\frac{1}{2n_{\mathrm{I}}}<\frac{\Lambda}{\lambda}<\frac{3}{2n_{\mathrm{III}}} \qquad (1)$$

where n_{I} and n_{III} are the superstrate and substrate refractive indices respectively (incidence from superstrate), Λ is the grating period and λ is the considered (vacuum) wavelength. Moreover, $n_{\mathrm{III}} > n_{\mathrm{I}}$ is assumed. In

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the following, for convenience, the reflected and transmitted orders will be signified by m R and m T for reflected and transmitted orders, where m is the order, e.g. -1 T for -1st transmitted order and 0R for the 0th reflected order. The lower limit of Eq. (1) is determined by grazing incidence and diffraction of -1R, while the upper limit is determined by emergence of -2 T. For higher dispersions, Λ/λ approaches the lower limit, the angle of incidence rises according to the grating eq. and the maximum obtainable transmitted efficiency is mainly limited due to a Fresnel-like loss into the reflected orders. Calculation of the energy distribution into the diffracted orders in the regarded highly dispersive domain requires rigorous electromagnetic methods, i.e. solving Maxwell's Eqs. [13]. Over the last decades, different approaches have evolved. In the current paper, we use a self-implemented version of the Rigorous Coupled Wave Analysis (RCWA), that also comprises tools for optimizing and tolerancing the grating profiles for manufacturing. The RCWA is a well-established, versatile and robust tool for rigorous numerical solution of the diffraction problem especially suited for dielectric gratings with moderate refractive index contrast [14–16].

In Fig. 1, a binary grating etched into a dielectric substrate with $n_{\mathrm{III}} = 1.45$ (fused silica at 1030 nm) is considered. The maximum possible -1st transmitted diffraction efficiency is plotted as a function of Λ/λ. The data was determined numerically by sweeping the full parameter space (duty cycles from 0 to 1 and depths from 0 to 5 μm with 101 × 101 samples, Λ/λ with 103 samples), using RCWA with 15 orders. For small periods, reflection losses cause a drop, especially for TE-polarization. For TM, there is a maximum for incidence angles close to Brewster's angle. However, significantly deeper grooves are necessary compared to TE, making gratings optimized for TM difficult to manufacture.

A comprehensive model based on the true modal method [17] can physically explain the fundamental diffraction mechanism for Bragg transmission gratings. In summary, the mechanism is as follows: The fields inside idealized binary grating layers are decomposed into laterally periodic waveguide modes. For the TE and TM polarized components of the incident field and a given angle of incidence, each of the waveguide modes has a characteristic field distribution and an effective refractive index that is a function of the duty cycle. The excitation efficiencies of the modes are determined by mode matching with the incident field. At the interfaces, there are reflection losses due to an effective refractive index mismatch. If only two modes propagate in the grating region, Littrow diffraction can be considered a two-beam interference. Due to their effective index difference, the modes accumulate a phase difference and interfere at the output port to excite the transmitted diffraction orders resulting in a characteristic sinusoidal efficiency over the grating depth. From symmetry reasons, maximum efficiency in the -1st transmitted order is achieved for a phase difference between both grating modes of $(2m + 1)\pi$, while obviously for $2m\pi$, the zero order efficiency is maximum. Again, it has to be stressed that the effective index jump is the main physical cause for undesirable reflection losses giving a lever for improvement.

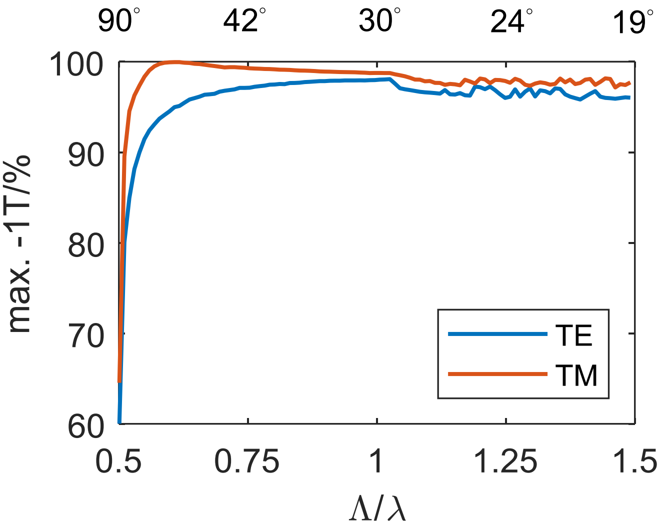

Fig. 1. Maximum possible diffraction efficiency as a function of period-to-wavelength-ratio Λ/λ for -1st transmitted order using binary gratings and Littrow incidence (incidence angles indicated above). Substrate and groove refractive index $n = 1.45$ (fused silica at 1030 nm). For $\Lambda/\lambda > 1.034$, the second transmitted order appears and the two-beam-interference analogy fails, resulting in a less smooth energy distribution into the regarded order.

To address the mentioned losses and achieve high efficiencies in the desired order, one can in principal use different approaches that have partially been proposed in the literature. To illustrate their merits and drawbacks we consider the design of a 1700 l/mm grating on a fused silica substrate optimized for a small bandwidth around 1030 nm, which is a typical femtosecond laser line (Yb:YAG/Yb:fiber). Theoretical spectral efficiency curves for different design approaches and TE polarization are depicted in Fig. 2. They will briefly be discussed in the following. Please note that the designs presented here just serve as examples and do not necessarily signify the theoretical limits for each approach. However, for comparison they were optimized to achieve high efficiencies and hence, also the profile depths as a crucial optimization parameter vary. The given example yields $\Lambda/\lambda \approx 0.57$ and a maximum -1 T efficiency of 93.2% for the aforementioned monolithic binary approach and TE polarization with the spectral efficiency plotted in Fig. 2. Obviously, according to Fig. 1, one approach would be to optimize the grating for TM polarization (maximum efficiency of 99.94% for a monolithic binary grating). However, the profile parameters for this maximum (height 4.9λ, duty cycle 0.82) are extremely uncomfortable for manufacturing and the period has to be fixed for Brewster incidence.

Another method (not included in Fig. 2) would be to encapsulate the grating in the substrate material to reduce the effective refractive index jump and cancel remaining reflected orders by destructive interference at the binary layer's interfaces [8]. Reflection from the remaining planar substrate-air interfaces can mostly be eliminated by using thin film anti-reflection coatings. In addition to being able to reach close to 100% efficiency, another advantage is the protection of the grating from dust and mechanical damage. However, though different methods for encapsulation have been proposed [18,19], the processes are rather cumbersome and susceptible to defects.

High efficiencies for -1 T can also be achieved with binary profiles by adding a dielectric multilayer stack underneath the corrugation to suppress reflected orders [20]. Optimization of the grating and the multilayer stack then has to be completed in one step using rigorous methods because multiply diffracted orders contribute to the overall efficiencies. Hence, classical thin film design programs are unable to solve the problem. Another drawback of this approach, to our experience, are the extremely small tolerances for the film and grating parameters that make their serial production difficult without sophisticated trimming processes. The example in Fig. 2 was optimized using a genetic algorithm with the (binary) grating etched into the last of a four layer alternating SiO_2-HfO_2 stack and film thicknesses, grating depth and duty cycle as the optimization parameters resulting in a maximum efficiency of 98.6%. Even higher efficiencies can be achieved by using a larger number of layers of optimized thickness.

Another possible approach that has, to the best of our knowledge, not been published yet is placing additional sub-wavelength structures on top of the grating. These structures can be periodic or randomly distributed and just like the well-known biomimetic antireflection gratings ("Moth eyes") [21], reduce the effective refractive index jump by artificially creating intermediate refractive index steps or even a continuous transition due to their duty cycle while being zero-order in spatial frequency. Designs and realizations based on this approach could easily be subject to another paper and we restrict ourselves to the remark