Journal of the European Optical Society - Rapid Publications 2, 07024 (2007) www.jeos.org

High-efficiency wide-band metal-dielectric resonant grating for 20 fs pulse compression

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More than 95% average efficiency TE-polarisation diffraction over a 200 nm wavelength range centred at 800 nm is obtained by a metal-dielectric grating structure with non-corrugated mirror. 98% maximum -1st order diffraction efficiency and a wide band top-hat spectrum are demonstrated experimentally opening the way to high-efficiency Chirped Pulse Amplification of femtosecond pulses as short as 20 fs. [DOI: 10.2971/jeos.2007.07024]

Keywords: femtosecond laser, compression gratings, leaky mode

1 INTRODUCTION

Flux resistance of the pulse compressor gratings is the most critical stage of a Chirped Pulse Amplification (CPA) scheme [1]. State of the art femtosecond compression gratings [2] exhibit a low damage threshold as they usually consist of a gold layer deposited onto an undulated organic film [3]. A sinusoidal metal grating is known to exhibit high diffraction efficiency, by means of a fabricable shallow corrugation, for the TM polarisation only; high diffraction efficiency for the TE polarisation requires very deep grooves. When this incidence configuration is used with high energy pulses problems may arise since any surface imperfections may excite local plasmons. Originally it was suggested to use an all-dielectric structure composed of a multilayer mirror with a dielectric corrugation on top [4] as an alternative. This motivated further developments [5, 6] which, in the mid-nineties, led to the demonstration of large dielectric gratings at 1050 nm wavelength capable of withstanding significantly higher flux [7]. Since around 2000 the company Jobin & Yvon have also developed commercial elements [8]. With the development of Ti:sapphire industrial lasers for machining in the 800 nm wavelength range [9], new grating specifications have emerged such as high average power. This is as a consequence of higher repetition rates as well as the restricted bandwidth over which an ultimate diffraction efficiency can be reached in the 4-pass schemes currently used. This makes the overall system efficiency very loss sensitive. An all-dielectric solution exists which exhibits a flat top diffraction efficiency spectrum over up to 40 nm [10].

The search for ever shorter pulses in advanced high energy physics gives rise to new bandwidth specifications [11] which all-dielectric gratings can not fulfil. The rationale prevailing in the solution of references [12, 13] will be used to obtain a diffraction efficiency as close as possible to 100% over a very broad wavelength range; plane metal mirror will be used instead of a multilayer mirror since the former ensures an almost constant reflection phase shift which permits broadening in the spectral domain around 800 nm where leaky mode resonance can be satisfied [13]. The present paper describes the operation of the proposed metal-dielectric grating and gives experimental results for a structure fabricated on small substrates by means of an adapted process, that agree with the expected characteristics.

2 GRATING DESIGN

The basic grating structure is represented in Figure 1. It is comprised of a metal mirror and a dielectric multilayer with a corrugation in the last layer at the air side. The diffraction is produced by the sole -1st order in a contradirectional scheme away from the Littrow condition.

As shown in Ref. [13] the condition for high efficiency is given by the dispersion equation of a TE leaky mode excited by refraction of the incident wave in the corrugated layer. The rationale behind this is the following: the reflection of an incident wave by a mirror based dielectric film is composed of two contributions: the reflection from the top of the dielectric film, and the reflection of the wave having penetrated into the film by

Received June 1, 2007; published August 7, 2007 ISSN 1990-2573

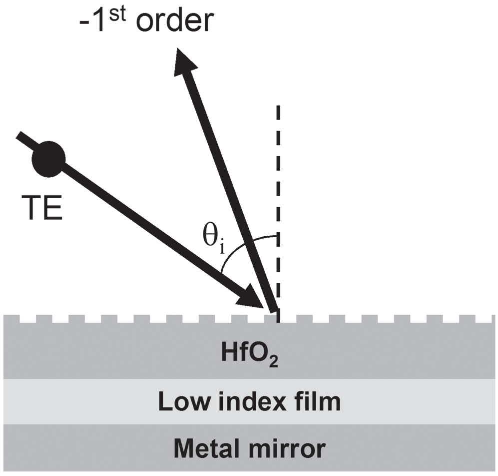

FIG. 1 Cross-sectional view of the metal-mirror based multilayer with binary corrugation in the last layer. TE incidence is at angle θ_i, resulting in diffraction only along the -1^{st} order.

refraction through its top interface from the mirror. These two contributions sum vectorially in the incident medium in the direction of the Fresnel reflection. If the condition for constructive self-interference of the refracted wave in the dielectric film is meet, its field is partially trapped in the film in the form of a leaky mode. Under this condition, the two contributions to reflection are of opposite sign. This has the important consequence that the Fresnel reflection can be cancelled if the moduli of the two contributions can be made equal. The presence of a periodic grating corrugation at the film-air interface decreases the field reinforcement in the film and diffracts the incident wave in the direction of the -1^{st} order. There is a certain grating strength for which the Fresnel reflection is cancelled by destructive interference between the two components and consequently 100% of the incident energy is diffracted. Such phenomenological understanding of resonant diffraction does not depend on the polarisation. However, the capability of the dielectric film to trap the incident field is not the same for the TE and TM polarisations. The presence of the Brewster effect on the TM polarisation restricts the possibility of achieving the cancellation of the Fresnel reflection, therefore the TE polarisation is usually preferred. Such resonant diffraction effects are not limited to a single film dielectric structure. If the leaky mode propagating structure on top of the mirror is composed of several layers, the same rationale applies (see Figure 2). The leaky mode dispersion equation is more complex, but it is easy to derive as shown in Ref. [12].

In the present spectral broadening problem there is not much benefit in having a large number of dielectric layers on top of the metal mirror because the grating would then excite a number of true guided modes of the multilayer waveguide bounded by the metal substrate and the air medium. This is especially so if the femtosecond pulses are very short (for instance 20 fs), meaning the equivalent bandwidth is very broad. A spectral band without waveguide mode excitation is needed, which can easily be achieved with a restricted number of dielectric layers. The minimum number of layers is actually one; that in which the grating corrugation can be

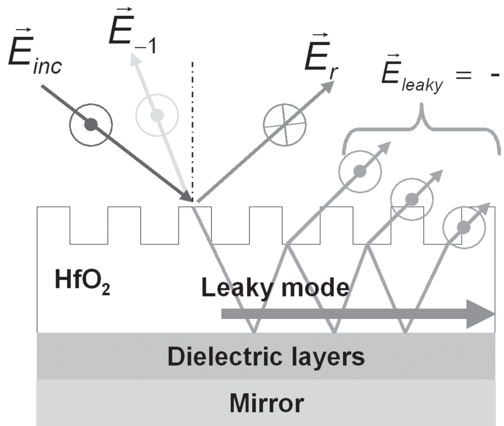

FIG. 2 Representation of the cancelling of the Fresnel reflection by balanced destructive interference between top reflected field and re-radiated leaky mode field. The circles with cross and dot represent the orientation of the electric field.

etched. A metal thin film may however have to be protected by a specific dielectric coating and it is also advantageous to make the grating in a high refractive index layer so as to increase its strength without having to etch the corrugation too deeply. A two-layer system above the metal mirror thus seems to be a suitable configuration: a thin protection layer of index n_p and thickness t_p and a corrugated high index layer of index n_g and thickness t_g. For this simple two-layer system the leaky mode resonance condition can be written analytically :

$$\kappa_p \cdot \tan\left(\kappa_p t_p - \frac{\phi_a}{2}\right) + \kappa_g \cdot \tan\left(\kappa_g t_g - \frac{\phi_m}{2}\right) = 0 \qquad (1)$$

where $\kappa_p = k_0\sqrt{n_p^2 - n_c^2 \sin^2\theta_i}$ and $\kappa_g = k_0\sqrt{n_g^2 - n_c^2 \sin^2\theta_i}$ with $k_0 = 2\pi/\lambda$ at vacuum wavelength λ and θ_i is the incidence angle in medium of index n_c. The phase terms ϕ_m and ϕ_a are the reflection phase shifts at the metal boundary and at the air side with incidence from the leaky mode propagating layer side respectively. ϕ_a is zero since the transmission medium (air) has lower index, and ϕ_m is approximately given by:

$$\phi_m \cong \pi - arctg\left(\frac{2\sqrt{n_p^2 - n_c^2 \sin^2\theta_i}}{\sqrt{-\epsilon_{mr}}}\right) \qquad (2)$$

in the case of a low loss optical metal (gold or silver or aluminium) of complex index $\epsilon_m = \epsilon_{mr} - j\epsilon_{mj.}$

The resonance condition must be satisfied in the actual structure comprising the corrugation. The latter is accounted for by considering it as an equivalent homogeneous layer having the same thickness t_g (i.e. the corrugation depth) and an equivalent index n_{eq} given by the expression

$$n_{eq} = \sqrt{\varepsilon_\ell \cdot \frac{w_L}{\Lambda} + \varepsilon_s \cdot \frac{w_s}{\Lambda}} \qquad (3)$$

which holds well in the case of the TE polarisation. The value w_L is the grating line width made of permittivity ϵ_l and the grooves of permittivity ϵ_s have a width w_s. The period is denoted Λ.

A design example will now be given with a silver mirror ($\epsilon_m = -28 + j1.5$ at $\lambda = 800$ nm), a protective layer of Al_2O_3

(n_p = 1.65) and a HfO_2 corrugated layer (n_g = 2.12 at λ = 800 nm). The incidence angle in air is 50 degrees. From expression (3) the hafnia layer has an equivalent index n_{eq} = 1.657 assuming a 50/50 corrugation line/space ratio.

Inputting this data into an exact code based on the modal method [14] gives the diffraction efficiency spectrum of Figure 3 curve a). Close to 90% diffraction efficiency is obtained with 6.6% in the zero order. The missing 3.8% is lost in the metal substrate. The resonance is broad as usual with a metal mirror, however the top hat character is not yet present.

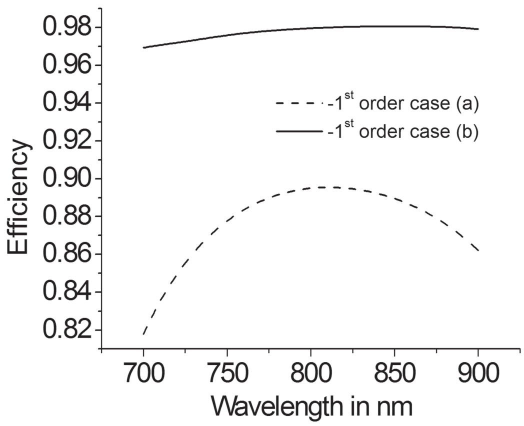

FIG. 3 a) -1st order diffraction spectrum with corrugated two-layer structure of unity line/space ratio satisfying the leaky mode dispersion equation. b) -1st order diffraction spectrum with optimised binary corrugation etched through the hafnia layer.

Using Lyndin's optimisation code [14] to model the phenomenologically designed structure gives a final structure which achieves the highest diffraction efficiency over the requested spectral width which is here 200 nm centred at 800 nm wavelength. The optimisation code uses a standard multivariate search procedure where the core of the code is a direct problem analysis based on the "true-mode method" [15]. This method forms the electromagnetic field from a basis of the modes of the corrugation, as the physical actuality, instead of decomposing the corrugation in to Fourier harmonics. The objective function to be optimised is the -1st order diffraction efficiency over a given spectral range. With the refractive index of the layer materials and the metal permittivity being known and the incidence angle being imposed, the optimisation starts when two layer thicknesses approximately satisfying dispersion Eq. (1) are input. The optimisation code must be somewhat assisted to deliver a structure which is still fabricable. Left to itself the optimisation process tends to lead to the suppression of the necessary protective layer of the metal film and/or to an aspect ratio of the hafnium oxide lines which is too large. To account for technological limitations the relevant critical parameter(s) are removed from the set of optimisation variables and are instead controlled directly by the user of the code. Figure 3 curve b) is the optimised diffraction efficiency spectrum produced by a corrugation of adjusted line/space ratio (smaller than 1) and 580 nm period. The same code also permits tolerances to be set.

3 EXPERIMENT

As compared with standard metallised gratings, the fabrication of the above designed structure is quite a challenge. Silver was chosen for its slightly lower losses. Aluminium was ruled out due to the large losses it suffers. It was feared that the adhesion of the dielectric layers on to a gold film would be too weak. The silver protection layer is aluminium oxide. There are two big technological difficulties: the first one is to make the lithography on such a highly reflecting surface, and to achieve a small line/space ratio. The second problem is the rather deep dry etching required. The hafnia layer must be etched down to the protective layer without physically or chemically damaging the silver surface. Yet another difficulty is the removal of the resist rest. These difficulties were however provisionally solved. Instead of using a thick ARC to isolate the resist layer from the highly reflecting silver layer [16, 17], a 30 nm-thick layer of CuO was used. This decreased the reflection to below 40% which was sufficient to adjust the two lithographic steps leading to a small line/space ratio. Figure 4 is the AFM scan of a resist grating obtained under adequate exposure conditions. The resist ridges are slightly rounded due to the presence of a standing wave field node close to the top of the resist layer.

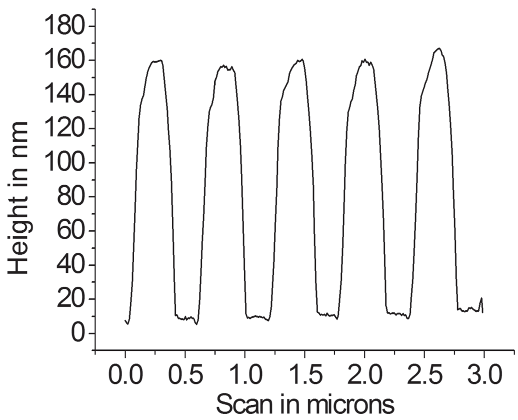

FIG. 4 AFM scan of a small line/space ratio resist grating on top of the CuO layer.

The thin CuO layer at the bottom of the resist grooves was opened by wet etching in vinegar. The RIBE etching conditions were adjusted to further reduce the thickness of the resist walls down to the hafnia layer. Figure 5 is the AFM scan of a typical corrugation obtained in the hafnia layer. The reactive component of the etching process is large enough to only require a short etching time meaning resist rests are easy to remove by wet chemistry.

The 25 mm diameter, 6 mm thickness corrugated wafers were tested by means of a CW tunable Ti:sapphire laser under an incidence angle of 50 degrees between 710 and 840 nm wavelength which was the available tuning range. As shown in Figure 6, the -1st order diffraction efficiency is 95.7% on average and is remarkably flat. The 0th order diffraction efficiency is 1.7% on average. Although the diffraction efficiency is already quite high, these results do not represent a limit. The first reason is that there were not enough samples to enable a screening of different line/space ratios. It is not excluded that a slightly different ratio could lead to a better extinction

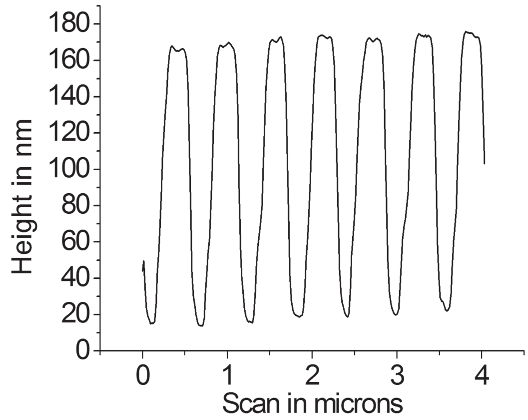

FIG. 5 AFM scan of a 580 nm period grating after RIBE through the hafnia layer and resist, and CuO removal.

of the 0^{th} order. The second reason is that the silver layer was slightly damaged during deposition by a mechanism which was later identified and which can be corrected with an expected decrease of the losses.

Summarising the outcome of the experimental section, it can be stated that the difficult lithography and etching processing of a silver film containing structure has been basically solved, that the wafer scale uniformity of the diffraction efficiency is within a few percent, and that the damage caused to the silver mirror can be avoided which is likely to lead to an increase of the diffraction efficiency by a few percent.

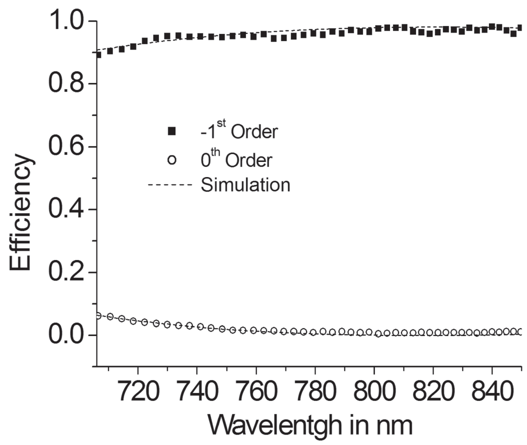

FIG. 6 Experimentally measured -1^{st} order diffraction efficiency and 0^{th} reflected order spectra under 50 degrees TE incidence.

4 CONCLUSION

The evidence has shown that a compression grating of high efficiency and very wide band associating a flat metal mirror can be fabricated to match the demands of femtosecond laser CPA down to a 20 nm pulse duration. The most critical future step is the testing of the flux resistance which will be undertaken after the full CW characterisation has taken place.

Regardless of the outcome of the flux resistance tests, this new grating technology is already bound to find applications in domains where high efficiency and broad bandwidth are required without strong demands on the damage threshold.

The fabrication technology is difficult, however the present work has also allowed identification of fabrication steps which can lead to a major reduction in the production costs.

ACKNOWLEDGEMENTS

The authors are very grateful to J.P. Chambaret and F. Canova, ENSTA, for their guidance towards the objectives of high energy physics (ELI project), for their encouragements, and for preparation for the flux resistance tests.

Prof. F. Placido, Thin Film Centre of the University of Paisley, UK, is gratefully acknowledged for his assistance in identifying an absorptive layer and for depositing the thin CuO films on the metal-dielectric substrates.

The authors also want to thank Mrs Reynaud for her contribution in AFM characterisation, and Prof. A.V. Tishchenko for many enlightening discussions on the resonant diffraction effect used in such structures.

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