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Nanostructured blazed gratings for high-performance spectrographs

Simon Ans[a,b], Guillaume Demésy[b], Frédéric Zamkotsian[a], Andrei Mursa[c], Roland Salut[c], and Nicolas Passilly[c]

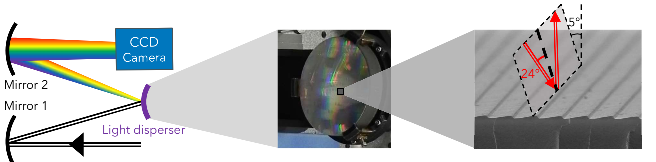
[a]*Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France*
[b]*Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, Marseille, France*
[c]*FEMTO-ST, CNRS, UFC, Besançon, France*

Abstract : We study the light disperser of a spectrograph, which is traditionally a blazed grating with a sawtooth profile. On the one hand, preliminary manufacturing results are presented. On the other hand, in order to find the optimal opto-geometric characteristics of this keystone device, topology optimization based on the Finite Element modelling of the Maxwell's equations is used.

Context of the project

Physical problem

The classical sawtooth blazed grating in reflection is a periodic pattern that mostly reflects the incident light on a particular diffraction order (for our case the order −1). It is widely used in spectroscopy and the goal of the new generation of spectrographs is to be more efficient though more compact.

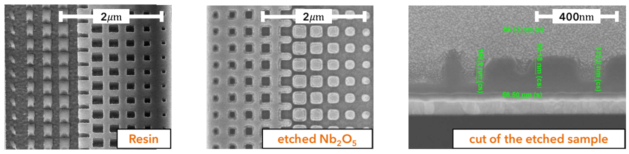


Offner spectrometer — *Traditional sawtooth blazed grating [1]* — *SEM view of the sawtooth blazed grating and angle specifications [1]*

Manufacturing metasurfaces

Optimizing the e-beam lithography

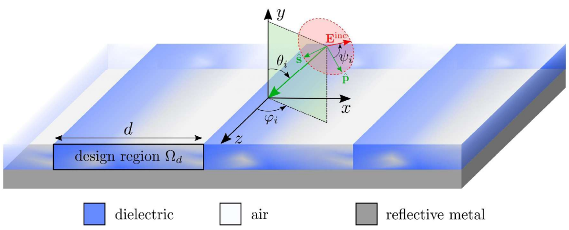
Starting from a 3D metasurface pattern developed by considering the phase shift induced by the sawtooth grating (Ans et al. OWTNM 2023), the strengths and constraints of the manufacturing of nanostructures are defined.
First samples of blazed gratings have been manufactured on an Nb_2O_5 layer of 150nm using **e-beam lithography** (RAITH Voyager lithography system) with **locally adjusted** electronic doses.



Theoretical model

Finite Element Method and topology optimization

At the nanometer scale, the grating can be seen as a **periodic** collection of diffracting objects with a pattern defined in the **design region**. The framework here is the **conical case**: the consideration of a 2D geometry where the incident plane wave parameters are let totally free [2]. Moreover the permittivity distribution within the design region is free as well.



The grating considered for the mathematical model

The problem is solved numerically using the **Finite Element Method**. The triangular discretization meshing and the numerical resolution are resp. supported by the open-source softwares Gmsh [3] and GetDP [4]. It enables to access the **diffraction efficiencies** R_n.

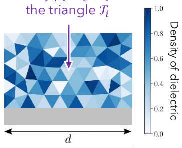
In **topology optimization**, on each triangle the dielectric permittivity depends on a design vector $\boldsymbol{\rho}$ constant per triangle of the finite element mesh through the SIMP method :

$$\varepsilon_r^d(\boldsymbol{\rho}) = (\varepsilon_{r,\max} - \varepsilon_{r,\min})\boldsymbol{\rho} + \varepsilon_{r,\min}.$$

The optimization problem is then, for a fixed diffraction order n :

$$\begin{cases} \max\limits_{\boldsymbol{\rho}} & R_n(\boldsymbol{\rho}) \\ \text{s.t.} & \text{Maxwell's equations} \end{cases}$$

It is solved using GCMMA [5] and the **Jacobian** of R_n is computed using the **adjoint method** [6].



Mesh-based density distribution using SIMP

In order to obtain a readable and realistic shape after the topology optimization, both filters presented below are necessary. Their (analytic) derivative is also implemented in the calculation of the Jacobian.

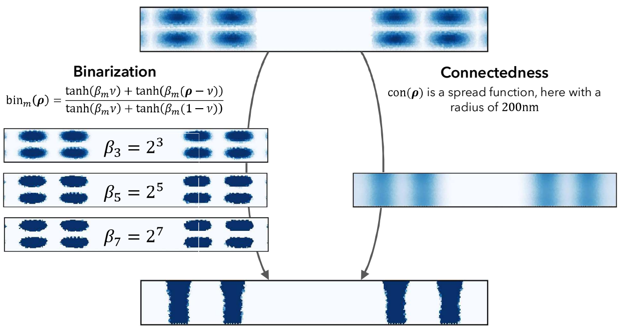
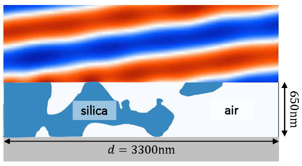


Illustration of the binarization and connectedness filters on a simple pattern

Numerical results

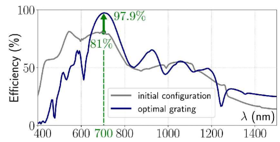
Optimizing blazed gratings

The optimization problem is first solved **on a single wavelength** in order to reach a diffraction efficiency close to 100%.



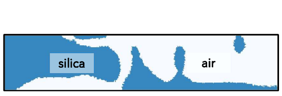
$\lambda = 700$nm, $\theta_i = 24{,}5°$, $\varphi_i = -11°$, $\psi_i = 90°$

Mono-wavelength optimization on a silica dielectric layer and projection of the scattered field at the targeted wavelength and angles



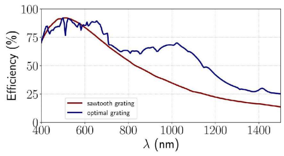
Spectral response in the -1st diffraction order as compared to the initial configuration

The **brodband optimization** outperforms the sawtooth grating on a wide range of wavelengths, so that the efficiency averaged on the interval [400,1500]nm reaches 80% instead of 52% with the traditional grating.

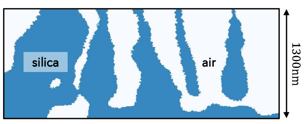


$\lambda \in [400{,}1500]$nm, $\theta_i = 24{,}5°$, $\varphi_i = -11°$, $\psi_i = 90°$

Broadband optimization

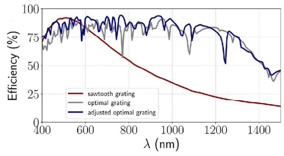


Spectral response in the -1st diffraction order as compared to the initial configuration and the sawtooth grating



$\lambda \in [400{,}1500]$nm, $\theta_i = 24{,}5°$, $\varphi_i = -11°$, $\psi_i = 90°$

Broadband optimization for a twice higher design



Spectral response in the -1st diffraction order

Conclusion

A totally **open-source topology optimization code** has been implemented with mathematical calculations of the tools for the gradient descent. It enables to generate designs of **blazed nanostructured gratings** made of a dielectric layer. The results show an improvement of the diffraction in the **infrared region**, which has now to be confronted to the manufacturability contraints.

Aknowledgements

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