Structured Meta-Mirrors for Beam Spatial Filtering

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ABSTRACT
The work presents optical spatial filtering in reflection based on translationally invariant meta-mirrors. The meta-structure is generated by a thin grating presenting a transverse modulation of the refraction index on the sub-micron scale located in front of a mirror. We analyze the angular spectrum of the reflected waves for different types of structured meta-mirrors as well as the filtering effects of these meta-structures in reflected beams. The comparison between FDTD simulations of full Maxwell equations and different approximated models allows to determine the filtering contribution from the structured cavity and from Mie resonances associated to elements generating the grating.
Keywords: meta-mirrors, structured mirrors, spatial filtering, beam shaping.

1. INTRODUCTION

Spatial filtering is commonly performed by confocal arrangements of lenses with a filtering diaphragms at the focal plane. These filters sharply cut the far-field intensity profile and correspondingly modify the light beam profile in direct space. Conventional lasers, among other optical setups, contain this type of spatial filters in different intracavity configurations for the improvement of the spatial characteristics of the laser radiation. This limits the energy enhancement of high transverse modes ensuring the laser emission on the lowest modes that benefits from the whole pump energy excitation. The desired consequence is an enhancement of the beam quality and brightness. Apart from this conventional filtering method, other methods based on external gratings or external feedback schemes have been proposed although with some inconvenient due to their large size, the necessary alignment precision and the compactness reduction [1]. The spatial filtering solutions become more critical in the case of Broad Area Semiconductor lasers, VCSELs and microchip lasers, where external filtering schemes and conventional confocal lens severely reduce their compactness.

Intracavity Photonic Crystals (PhCs) as an alternative method for spatial filtering was recently proposed [2,3]. While the method showed efficient filtering in a single transmission scheme, also for intracavity arrangements [4,5,6], the fabrication of such PhC filters is still technically challenging because of the necessary periodic modulation of the refractive index along the light propagation direction and transverse directions. Therefore, 2D PhCs are required for 1D spatial filtering in devices with unidimensional transverse directions like Edge Emitting Lasers but more commonly 3D PhCs are necessary as is the case of microchip lasers, VCSELs or classical lasers. The fabrication of such structures, with sufficient index contrast, size and precision represents a real challenge for nowadays technologies. Up to now, experimental demonstration of PhC spatial filtering, has only been achieved with structures fabricated by direct laser writing technologies, that is to say writing, point by point, organic and nonorganic materials [7,8].

An ideal filtering component would be a thin and flat spatial filter convenient not only for its size but also for fabrication purposes, although, the longitudinal modulation is necessary for the spatial filtering. A compromise arrangement would be a 2D thin grating positioned parallel and close to a totally reflecting mirror. A possible configuration is a structured layer or phase mask positioned very close and parallel to the mirror surface holding some of the features of a PhC spatial filter. The structured mirror involves different intertwined optical effects as scattering from the grating, interferences from the Perot -Fabry (PF) cavity and Mie resonances from the elements composing the grating.

The flat meta-mirror arrangement has to be treated as a Perot-Fabry (PF) resonator composed by the mirror and the structured layer. The unfolded PF resonator is equivalent to a finite-length PhC and its effective length directly depends on the resonator finesse mainly given by the refractive index contrast of the structured layer due to the mirror reflectivity is unity. The filtering efficiency – the depth and width of the spatial filtering dips – remains an open question.

2. TRANSVERSE STRUCTURED MIRRORS

We model the structured mirror as a row of equispaced rectangular elements with a given thickness in front of a flat totally reflecting mirror generating a system of two nested cavities with transverse structure, Fig. 1.

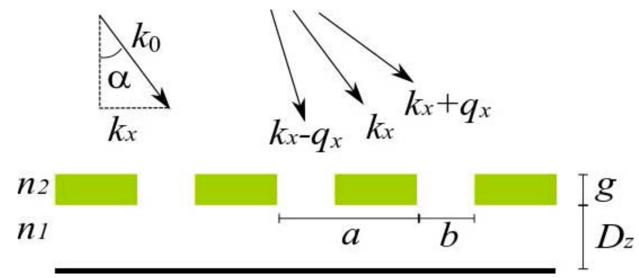

Figure 1. Model of a meta-mirror composed by a structured layer faced to a mirror. The structured layer is made of equispaced rectangle elements with transverse periodicity a and separation distance b. The refractive index of layer elements and spacer are n_2 and n_1 respectively.

The structured layer composed by rectangles of thickness *g* and refractive index n_2, can be considered as a pair of shifted diffraction gratings with period *a* embedded in a medium with refractive index n_1. One grating is associated to the rectangular elements, each one considered as a PF cavity with refractive index n_2 and thickness *g*. Transmittances and reflectances of these elements are given by Fresnel relations and phase-shifts associated to the cavity. The second grating corresponds to the slits of width *b* between the rectangular elements. The mirror and the structured layer creates the main PF cavity of thickness D_z and refractive index n_1.

The model considers the field expansion into three principal transverse modes, zero- and first diffraction orders, all coupled through diffraction given by the structured layer with a grating wavenumber $q_x = 2\pi/a$. The field is written in vector form as $\vec{E} = \left(E_{k_x+q_x}, E_{k_x}, E_{k_x-q_x} \right)$ where subindices correspond to the involved transverse components. The field reflected from the structured mirror depends on the incident angle and can be written as

$$\vec{E}_{\mathrm{Re}f}(k_x) = \left[\hat{R} + \hat{T}\hat{P}\left(1 + \hat{R}\hat{P}\right)^{-1} \hat{T} \right] \vec{E}_0 \tag{1}$$

where $\hat{R}$ and $\hat{T}$ are the complex reflection and transmission matrices of the structured layer. The light propagation between the structured layer and mirror is modelled by matrix $\hat{P}$.

The response of the meta-surface is characterized by the reflection of the zero diffraction order, second component of the reflected vector $\vec{E}_{\mathrm{Re}f}(k_x)$. The meta-surface response in reflection involves optical diffraction, cavity interferences and scattering all controlled by the transverse structure and the involved optical distances in the longitudinal direction given by the thickness of the rectangular elements, *g*, and the mirror distance *Dz*.

For low refraction index contrast, a small refractive index differences between the rectangular elements and the surrounding medium, the grating is mainly supposed to transmit (reflection is not relevant). In this case, the arrangement is equivalent to two gratings, the real one and the image formed by the mirror, separated twice the distance to the mirror surface and the system is modelled just considering the scattering associated to both layers. Simple analysis give expressions for the zero-order reflection showing its dependence on the Talbot length $D_{zT} = 4\pi k_0 / q_x^2$.

For larger refractive index contrasts, the reflection becomes highly dependent on the incident angle and filtering properties of the meta-mirror are enhanced. The angular spectrum and filtering properties are characterized as a function of main parameters obtaining a good correspondence to precise FDTD calculations.

3. SPATIAL FILTERING

The angular spectrum is characterized by scanning *g*, the thickness of the rectangular elements, *Dz*, the structured layer-mirror distance and the optical wavelength. The zero-order reflection shows fringing associated to resonances in the main cavity when the cavity length *Dz* is scanned (Fig. 2a). In addition to these resonances, the rectangular elements introduce Mie resonances also affecting the response in reflection. Near Mie resonances the spectrum fringes corresponding to the main cavity loos contrast due to the decrease of the effective reflection in the structured layer and the corresponding reduction of the cavity finesse. Moreover, the finesse reduction also decreases contrast in the whole the angular spectrum and its potential capabilities for angular filtering.

The model is used to characterize the spatial filtering of an entering Gaussian beam (Figs. 2b, 2c) and their comparison with the filtering profile obtained with FDTD simulations of full Maxwell equations (Fig. 2d). These changes can be considered to obtain spatial filtering for given entering light wavelength.

The system linearity allows to predict the improvement of the beam quality for a noisy reflected. Numerical results show a strong noise reduction in reflection with an improvement of the beam quality. Maximal reductions of the beam quality factor M^2 reaches a factor of 2, that is in good agreement with theoretical predictions from the analytical model for a low contrast refractive index.

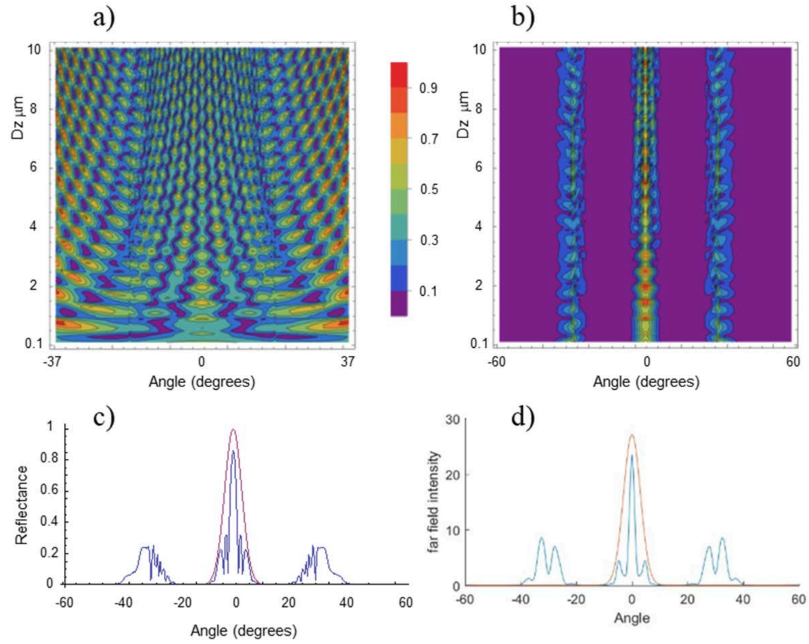

Figure 2: (a) Angular spectrum of the zero-order reflection as a function of the mirror distance Dz with $\lambda=1\mu m$, $g=0.4\mu m$, $n_1=1$, $n_2=1.68$; (b) Angular spectrum for a $3\mu m$ wide Gaussian beam reflected in a structure with the same parameters in (a); (c) Angular filtering profile for the same parameters and $Dz=9.5\mu m$; (d) Far field intensity for the same parameters of (c).

4. CONCLUSIONS

In conclusion, we introduce a new kind of structured mirror in the micrometric scale, meta-mirror, to obtain angular filtering using a translationally invariant linear system. A simple analytical model only considering scattering from the structured layer and its image predicts filtering features even for low contrast refractive index configurations. For higher contrast configurations a more elaborated model allows to analyze the angular spectrum in reflection. The filtering capabilities are demonstrated by reflecting an entering Gaussian beam obtaining angular filtering profiles in agreement with far field intensities from FDTD simulations of the full Maxwell equations. The filtering spectrum predicts beam quality factor M^2 to be reduced in a factor 2.

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