Holographically microstructured gratings for high-performance spectrometers

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We present different design concepts for achieving a high efficiency over a broad wavelength range in spectrally analyzing high-performance spectrometers. Among these concepts are the spectral pre-selection, the material-dispersion tuning and the recycling of false light. The blazed grating structures are fabricated by interference lithography.

1 Introduction

Grating spectrometers with a high spectral resolution, typically less than 10 nm in the visible range, e.g., demand dispersion gratings that exploit the effect of blazing of light in a single diffraction order.

Applications such as laser scanning microscopes use spectrally analyzing modules for detection of fluorescence light. Blazed diffraction gratings are crucial components for achieving optimal optical performance.

In imaging systems, like immersion micro-objectives [1], e.g., blazed grating elements are an enabling technology that achieves optical performance which cannot be achieved with classical refractive elements only.

Nonetheless, diffractive gratings have one particular disadvantage over prismatic solutions: the distribution of energy among the spectrum strongly depends on the ratio of grating period to the wavelength within the spectral range of interest. There is only one wavelength, called the blaze wavelength, for which the diffraction efficiency attains a maximum at a typical value of 80...85%. At the edges of the spectral range, the diffraction efficiency may drop below 30%, which leads to a low signal-to-noise ratio in many applications, as the ones mentioned previously. This effect becomes worse with the spectral band width is increased.

2 The technological concepts

To overcome the drawbacks of efficiency distribution over the spectrum for blazed gratings, there are four basic technological concepts regarding the diffractive element: (a) scanning variable-polymer-grating spectrometers [2], (b) recycling of specular false light [3], (c) material-dispersion tuning [4], and (d) the concept of spectral pre-selection [5]. Another, though simple concept incorporates many spectrometer sub-modules with different grating pitches in one spectrometer optimized for each spectral sub-region, separately. The latter will not be discussed here.

2.1 The recycling loop

When using blazed gratings, the desired diffraction order is typically the +1st or -1st order. Neighboring orders, here the 0th and the +2nd or -2nd order, resp., gain more energy the more the wavelength differs from the optimum blaze wavelength. Moreover, because of possible imperfections of the grating structure, which will occur in particular if the profile is realized with interference lithography (i.e. holographical optical elements), the incoming light is not perfectly dispersed into the single wanted diffraction order. These two effects are the common origin of specular diffracted light, which is, on one hand, completely lost for detection, and, on the other hand, may reach the detector as stray-light.

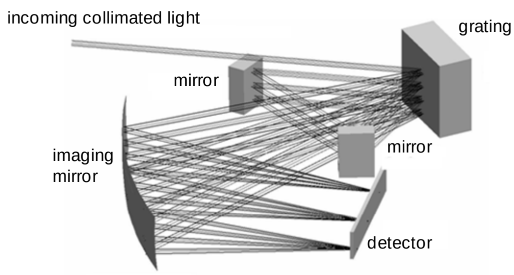

Fig. 1 *Recycling loop of the zeroth-order specular false light of a blazed grating.*

In the setup shown in Fig. 1 only one specular diffraction order (here the zeroth order) can be "recycled". So the grating is willingly designed away from the optimal blazing condition. The fraction of light which follows the 0th diffraction order is then gathered and redirected by two mirrors to the dispersion grating for a second time. One finds that only a few cycles are needed until most of the energy has been recovered in the wanted order and can now be used for efficient spectral detection.

2.2 The reflective double-grating

A different approach to compensate for efficiency reduction due to the mismatch of grating pitch with the wavelength during diffractive dispersion is the material-dispersion tuning.

In the special case of transmission gratings for imaging systems, Canon has shown that an effect known as "spectral achromatization" can be achieved by carefully choosing the combination of two microstructured materials with different Abbe's numbers in the design of an imaging diffractive element [6].

We have analyzed the case of reflection gratings for spectral applications [4]. The double-grating consists of two different diffractive structures, one metal grating filled with a low-index material n_1 and a second on top with a structured high-index material n_2 (Fig. 2). For the double-grating to achieve its desired performance, there are three basic constraints: the material dispersion given by the two refractive indices and the adapted structure heights d_1 and d_2 of each substructure.

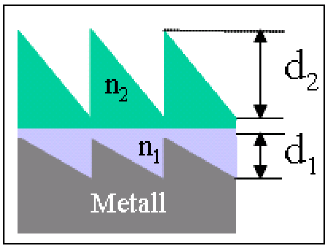

Fig. 2 *Material-dispersion tuning achieved by a reflective double-grating.*

However, for reflective double-gratings the grating pitch is typically about 500..1100 nm, and so each substructure is also constraint to a small structure height, preferably less than about 3 µm. Otherwise, the manufacturing of the profile structures faces large aspect ratios and becomes very challenging.

A careful and systematic material analysis involving both the Abbe's number and the relative partial dispersion revealed that two different polymers are required, where each possess a relative partial dispersion that differs from standard glasses which lie on the line of normal dispersion, the so called "normal glasses".

2.3 The spectral pre-selection

Classical spectrometer setups commonly use one single element for the dispersion of light. In this new approach the process of dispersion is separated into two steps, see Fig. 3.

The light that is entering the spectrometer will experience a first spectral splitting with a weak spectral resolution. Subsequently it hits the actual dispersion grating generating the high spectral resolution that is required for a certain application. Dependent on the method of the spectral "pre-selection", either a continuous spectrum or several separated spectral intervals can be created.

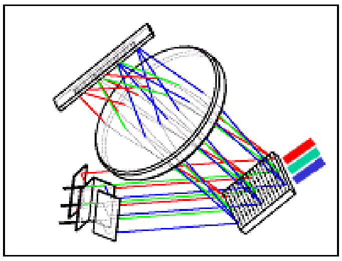

Fig. 3 *Spectral pre-selection by dichroic filters and structure-modulated diffraction grating.*

In addition, the dispersion grating is modified in such away that the profile height varies across the grating. Each fraction of the spectrum, which has been separated by the first splitting element, is now interacting with a different structure height at a different position on the grating. The efficiency of dispersed light can be maximized, if the local structure height is adapted to the blazing condition for each pre-selected part of the whole spectrum.

Acknowledgements

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