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Design Challenges in Micro-Optics

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Abstract: Micro-optics includes elements and systems fabricated by modern micromachining. It offers a large degree of freedom for the design. However, a deep knowledge of fabrication and characterization techniques is required in order to exploit the full potential of micro-optics.

Keywords: micro-optics, microlenses, microsystems, sub-wavelength gratings

1. Introduction

Micro-optics includes a family of optical components that are fabricated by modern micromachining, such as optical lithography, direct laser and e-beam writing, reactive ion-etching etc [1-3]. In the past decade micro-optics has emerged as a powerful tool to realize various optical functions that have not previously been possible or feasible using conventional optical elements. Elements utilizing either refractive or diffractive surfaces are now found in applications ranging from laser beam shaping in laser material processing to optical interconnects in telecom applications. One of the major strengths of micro-optics compared to conventional optics lies in the fact that micro-optics allows integration of large, complex optical systems into much more compact form. Additionally, emergence of replication techniques such as injection molding, allow the lost cost mass-production of micro-optical elements.

We will present different examples of micro-optics in order to discuss the degree of freedom, advantageous and limitations of miniaturization, and new opportunities.

2. Diffusers for illumination

Diffusers are interesting to study the design freedom of micro-optical elements [4,5]. For the application in illumination systems often a space-invariant response of the diffuser is required. In detail, the diffusers have to be almost independent on the size, the shape, and the homogeneity of the illumination. The utilization of arrays of microlenses with adapted geometry is straight forward for this application. The lenses generate the desired angular spectrum, while the array property warrants the space invariance of the element. We call these elements aperture modulated diffusers (AMDs), because the geometry of the aperture determines the shape of the generated far-field (angular spectrum). To use diffractive optics or computer-generated holograms (CGHs) has the advantage of higher flexibility for arbitrary structures and the deflection angles can be controlled very accurately. The drawback is the amount of light in the 0^{th}-order. An example of a calculated annular shaped far-field is shown in Fig. 1. The diffuser is assumed to be illuminated at a wavelength of $\lambda = 248$ nm by KrF-Excimer laser [4]. Besides AMDs, also beam-shaping elements can be applied. Their optical properties are calculated by iterative techniques [5]. Interesting is that the fabrication tolerances can be improved considerably by an optimized design.

Fig.1. Calculated far-field of an annular shaped pattern generated by an AMD.

3. Chromatic Aberration of microlenses

Miniaturization does not only change the size, but also the properties of elements. As example, we discuss the chromatic aberration and focal shift of microlenses. The refractive index of any transparent material is a function of the wavelength. Therefore, a lens made in one single material shows different positions of focus at each wavelength. The difference in position of these focal points is known as the longitudinal primary chromatic aberration. To correct this aberration, achromatic lenses are usually manufactured using two lenses of different material having different Abbe numbers combined to form a doublet. This method uses the different dispersion curves of the materials to obtain, at two well separated wavelengths, the same focal length with small variations for the other wavelengths in between. By their small dimensions microlenses can have low Fresnel numbers and then exhibit strong diffractive effects on the position and the shape of their focal point, as it has been extensively studied in the literature (focal shift [6]). We show here that for such lenses a range for the radius of curvature can be found where microlenses show an achromatic behavior [7]. These lenses are achromatic, because refraction and diffraction have opposing effects on the focal length. The presented results are of relevance for applications, where microlenses with small apertures and long focal lengths are used, for example, Shack Hartmann wavefront sensors or confocal microscopes.

4. Microsystems

Microfabrication enables the realization of complete systems [3]. A successful example is the miniaturized Fourier Transform Spectrometer (FTS) presented in [8].

Fourier transform spectroscopy is a well-known technique to measure the spectra of a weak and extended light source. The most common way of fabricating an FTS is utilizing a Michelson interferometer configuration with scanning mirrors. The output signal of the interferometer is the variation of the light intensity as a function of the optical path length.

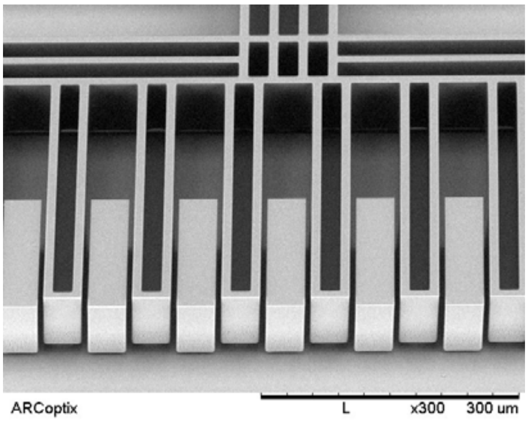

Fig. 2. Lamellar grating as used in actual products from ARCOPTIX (Neuchâtel).

A lamellar grating interferometer is a binary grating with a variable depth, which operates in the zero order of the diffraction pattern. A lamellar grating interferometer is used as an FTS, but, in contrast to a Michelson interferometer, which splits wave amplitudes at the beam splitter, a lamellar grating interferometer divides the wave front. It can be considered as a grating with variable depth (see Fig. 2). The displacement between the two series of mirrors determines the optical path difference (OPD). The original concept has been miniaturized based on MEMS technology [8].

A continuous scanning lamellar MEMS chip, as used today, is photographed in Fig. 2. The scanner is driven in resonance to move with best repeatability and high stability. First devices were capable to record visible light spectra by using a scanning range of 180 µm, recent devices allow up to 300 µm path difference corresponding to approximately 20 cm–1 resolution. The heart of the system is a Si chip of 5 times 3 mm^2. A single scan takes 2.5 ms and gives only limited signal to noise ratio due to low throughput caused by miniaturization. Averaging allows to bring up the signal to noise ratio to values as high as 20’000. Typical resonance frequencies are about 200 Hz. Si-InGaAs detectors enable a large wavelength range from 500 to 2600 nm.

5. Mid-IR photonics

Not only micromachining, but also devices and applications are important factors for the development of new domains. Quantum cascade lasers, for example, are compact light sources working in the mid-infrared (mid-IR). They are ideal light sources for sensor applications, because most of optical absorption spectral lines associated to the vibrational frequencies of gas molecules take place in the mid-IR domain of the optical spectrum. Mid-IR lasers offer also opportunities for diffractive optics, because the longer wavelength (compared to the visible spectrum) facilitates the fabrication of diffractive structures. Highly efficient binary sub-wavelength structures become attractive and feasible (see Fig. 3) [9]. A photonic crystal waveguide designed for gas monitoring in mid-IR is shown in Fig. 4.

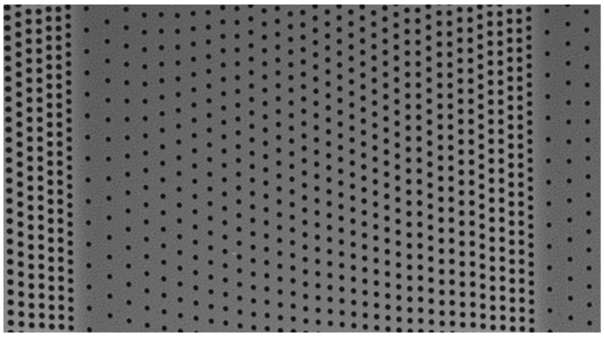

Fig. 3. Blazed binary grating designed for mid-IR wavelength (wavelength 5.2 µm, period 25 µm) [9**].**

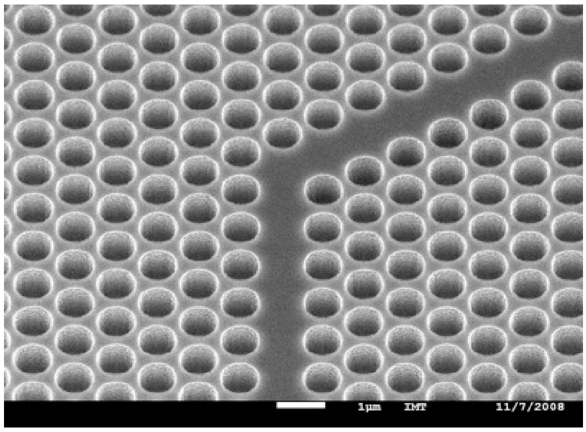

Fig. 4. Photonic crystal waveguide for mid-IR wavelength

6. Conclusions

The paper reviews interesting concepts for micro-optical elements and systems. Degrees of freedom for the design, miniaturization and limitations are discussed.

6. References

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