Microspectrometer with a concave grating fabricated in a MEMS technology

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Abstract

This paper reports on a microspectrometer using a concave grating fabricated in a MEMS compatible process. The fabrication technique is based on a standard lithography commonly used for pattern transfer onto a flat substrate. A planar grating structure is fabricated lithographically on top of a flexible membrane on a glass or silicon wafer and the membrane is subsequently deformed into a pre-defined shape using a master. The proposed technology had been used for the fabrication of the concave gratings for a microspectrometer composed of entrance slit, grating and image sensor. The fabricated microspectrometer demonstrates a subnanometer spectral resolution.

Keywords: Microspectrometer, concave diffraction grating, MEMS

1. Introduction

The development of miniature dispersion elements, detectors and optics is stimulated by the growing number of applications of compact spectroscopic devices. MEMS technologies, although not directly suited for the spectrometer fabrication, bring nevertheless new possibilities for designers1, such as miniaturization of the design eliminating the complex alignment of different spectrometer parts during the fabrication and integration of optics with photosensors and electronics. Since MEMS are intended for the mass production at low cost per unit, a spectrometer fabricated with MEMS compatible technologies has the potential for low unit cost as compared to conventional devices. Low cost would further increase the number of possible applications that the device can have.

Various spectrometers fabricated with MEMS technologies had been reported in the literature including Fourier Transform Spectrometers2 and Fabry-Perot tunable spectral filters3 as well as diffraction grating based spectrometers implemented according to classical principles4 or in a planar waveguide5. However, a spectral resolution below 1 nm over a wide wavelength range is difficult to achieve in practice. In small devices it is always desired to minimize the amount of different components and that is why in miniature spectrometers varied line-space (VLS) gratings combining dispersion and imaging functions are used for avoiding the collimating and focusing optics. MEMS
processing does not easily allow fabrication of non-planar structures and that is why compact spectrometer designs employ flat gratings which allow for the imaging with relatively small optical aberrations only in a narrow wavelength range. To decrease aberrations of the grating one has to limit the input aperture of the spectrometer or correct aberrations with the second planar grating. On the other hand a concave VLS grating introduces much smaller optical aberrations than the planar one and allows for larger input apertures. A standard technique for the fabrication of such gratings is holography. This technique however requires complicated optical recording setup and it can be difficult to satisfy tolerance requirements for the alignment of the setup components and a substrate where grating structure is to be recorded. Moreover, it is not always possible to realize the desired grating structure using holography.

The possibility of the fabrication of the concave gratings by replication of the grating structure on the concave lens surface from the elastomer master (“soft lithography”) and by laser direct writing were demonstrated. However those techniques do not allow for high throughput, since each grating is fabricated as a single component and there is no possibility for the integration of the grating with other components, if desired. The alignment of the elastomer master relative to the concave lens surface can also be challenging. This article describes a developed technology which overcomes the mentioned problems and possesses the advantages common to MEMS fabrication process. It is based on the planar lithography and thus is compatible with the MEMS processing allowing for the high throughput. The fabrication of the grating structure and its alignment is possible with the accuracy achievable in a standard lithography machine (mask aligner).

2. Concept of a microspectrometer based on a concave grating

The concept of a microspectrometer using a concave grating is shown in Fig. 1. The spectrometer includes a concave diffraction grating and a MEMS chip integrating the entrance slit and the array of photodetectors. This approach allows to obtain a highly compact system.

![Fig. 1. Concept of a microspectrometer based on a concave grating.](image)

The concept described had been implemented in Hamamatsu C10988MA microspectrometer. However, with a grating fabricated using soft lithography, spectral resolution of this spectrometer is limited to 12 nm.

3. Concave grating fabrication technology

The key idea of the proposed technology is the fabrication of the grating structure on top of a thin membrane formed on a glass or silicone wafer followed by the deformation of the membrane into the desired shape. Membranes typically used in MEMS (for example SiN) would not allow for such deformation and the only material flexible enough is a polymer. Although several techniques for the polymer membranes fabrication are possible (for example) the search for the simplest one resulted in the development of a process using a dry film resist as illustrated in Fig. 2.

The process starts with the lamination of the glass wafer with through holes at specified locations (left part of Fig. 2) with the dry film resist as demonstrated on the Fig. 2(a). For the simplicity only one hole is considered in the following discussion. OHKA TMMF negative film photoresist had been used, which was very easy to work with. However, the surface of the resist contains small scratches which can be 1– 20 μm in diameter and 0.1 – 0.5 μm
Such defects lead to light scattering. For the diffraction gratings this results in stray light or noise. In order to decrease the scattering effect a 3 \( \mu \text{m} \) thick layer of SU8 resist is spin-coated on top of the TMMF film to smooth its surface (Fig. 2(b)). Then the grating structure is made lithographically in the second SU8 layer which is 2 \( \mu \text{m} \) thick as presented in the Fig.1(c). As a next step the cavity under the membrane is filled with the epoxy adhesive and the wafer is glued to another one. The membrane is deformed with the plano-convex lens as illustrated in Fig. 2(d) and after epoxy is cured the lens is removed. Finally the grating is covered with a thin layer of aluminum for light reflection.

![Fig. 2. MEMS-compatible fabrication of concave gratings process steps.](image)

### 4. Experimental fabrication of the gratings and characterization of the microspectrometer.

The proposed technology had been applied to make test diffraction gratings. Figure 3(a) presents a part of the processed wafer containing two concave diffraction gratings. For the fabrication of the grating structure a simple lithography mask consisting of a number of equally spaced lines has been used. The grating period is 4 \( \mu \text{m} \) and the curvature radius is 25.8 mm. Thus the gratings structure is close to that one of a classic Rowland grating and the imaging properties of the produced gratings follow the imaging of the Rowland grating.

![Fig. 3. Part of the processed wafer with two gratings (a) and spectrometer experimental setup (b).](image)

Fabricated gratings have been tested in a spectrometer setup shown schematically in Fig. 3(b). Light from a Neon lamp was delivered to the grating using optical fiber with a 5 \( \mu \text{m} \) mode diameter and numerical aperture of 0.11. The cleaved fiber tip served as an input slit of the spectrometer and a CCD camera was used to capture diffracted light. Spectrum of Neon registered with the spectrometer is demonstrated in Fig. 4. Judging from the width of the spectral lines (FWHM) in Fig. 4 the resolution of the spectrograph is 0.9 nm (below 1 nm). The spectrum contains small false peaks or ghosts. This effect is explained by scattering resulted from the rough surface of the grating.

### 5. conclusions

A microspectrometer using a concave diffraction grating fabricated using a new technology had been characterized. The technology for the fabrication of non-planar optical components is based on a standard lithography and thus is compatible with the MEMS processing and preserves the all the advantages of a planar
lithography used for the fabrication of the flat diffraction optical elements. The fabricated gratings were used in a very compact spectrometer setup and allowed for the subnanometer spectral resolution in the visible range. Surface roughness resulted in stray light and ghost spectral lines, which makes the measurements of spectra containing weak spectral lines located close to the strong ones difficult.

Fig. 4. Neon spectrum registered with the fabricated microspectrometer.

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