

MEMS based systems and their applications in NIR spectroscopy for materials analysis

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Abstract Spectrometers and spectrographs based on scanning grating monochromators are well-established tools for various applications, for example analysis of organic matter. As new applications came into focus in the last few years, there is a demand for more miniaturized systems. The future spectroscopic devices should exhibit very small dimensions and low power consumption. A spectroscopic system with a volume of only $(15 \times 10 \times 14) \text{ mm}^3$ and a few milliwatts of power consumption, that has the potential to fulfill the demands of the upcoming mobile applications, has been developed. The approach is based on two major improvements. First, resonantly driven MEMS (micro electro mechanical systems) scanning grating chip, which provides also two integrated optical, slits and piezoresistive position detection has been used. Second, hybrid integration of optical components by highly sophisticated manufacturing technologies was applied. One objective is the combination of MEMS technology and a planar mounting approach, which potentially facilitate the mass production of spectroscopic systems and a significant reduction of cost per unit. The optical system design as well as the realization of a miniaturized scanning grating spectrometer for the near infrared (NIR) range between 950 nm and 1900 nm with a spectral resolution of 10 nm is presented. The MEMS devices as well as the optical components have been manufactured and first samples of the spectroscopic measurement device have been mounted by an automated die bonder. First application close measurements on organic matter have been performed and will be discussed.

1 Introduction

In the fields of medical analysis, food chain management, industrial measurement technology, many others Spectrometers and Spectrographs are well-established measurement devices. They facilitate a nondestructive quantitative and qualitative analysis of various kinds of substances, especially organic matter. Classical spectrometers and even modern compact systems exhibit a volume of a few hundred cubic centimeters and a few watt of power consumption [1–4]. In contrast, there is an increasing demand for miniaturized, potentially portable spectroscopic measurement systems. The design and manufacturing approach is based on two different strategies, miniaturization and hybrid integration. Key component of the spectrometer is a MEMS grating, which is based on a resonant electrostatic driving principle developed at Fraunhofer Institute for Photonic Microsystems (IPMS) [5]. In the latest generation, those MEMS contain not only a 1-d scanning grating plate and its electrostatic driving mechanism but also two additional optical slits and piezoresistive position detection. However, the task of miniaturizing the whole MEMS based system cannot be solved by simply increasing the functionality of the MEMS chip alone. Thus, hybrid integration of optical components by highly sophisticated manufacturing and assembly processes have been applied in a planar mounting approach using state of the art automated micro assembly production platforms [6]. The prototype of the miniaturized scanning grating spectrometer presented here has a volume of only $(15 \times 10 \times 14) \text{ mm}^3$, a very low power consumption and a measurement range in the near infrared (NIR) between 950 nm and 1900 nm at a spectral resolution of 10 nm . Application close measurements have been performed in the area of plastic material selection, where different kinds of plastic waste can easily be discriminated by NIR spectroscopy. Further measurements were made in the food quality business. For water, sugar and alcohol a more sophisticated chemometric model has been implemented. The analysis of honey samples showed not only the quantitative estimation of the water content but also insight to the sugar matrix (glucose, fructose, sucrose). On samples of spirits, the alcohol content has been measured. Here, the measurement accuracy was only affected by temperature, as is well known for the water-ethanol system. Other applications have been considered but not yet evaluated in detail, e.g. fruit freshness, meat watercontent, etc.

2 Optical systems design

Starting point of the optical design was the well-known Czerny-Turner setup which features two separate mirrors for collimating and refocusing, respectively while the Fastie-Ebert monochromator has only one large single spherical mirror [7–12]. The Czerny-Turner configuration offers more degrees of freedom for aberration correction, since the surface shapes and positions of the two mirrors can be chosen independently. An exemplary Czerny-Turner Monochromator is illustrated in its original version in fig. 2.1 (a). The electromagnetic radiation entering through an entrance slit (S_1) is collimated by a mirror (M_1) and subsequently impinges on a rotatable diffraction grating (G). The polychromatic radiation is spectrally dispersed by the grating and then refocused on an exit slit (S_2) by a second mirror (M_2). The exit slit cuts out a narrow part of whole spectrum. As the grating rotates, the spectrum is scanned across the slit.

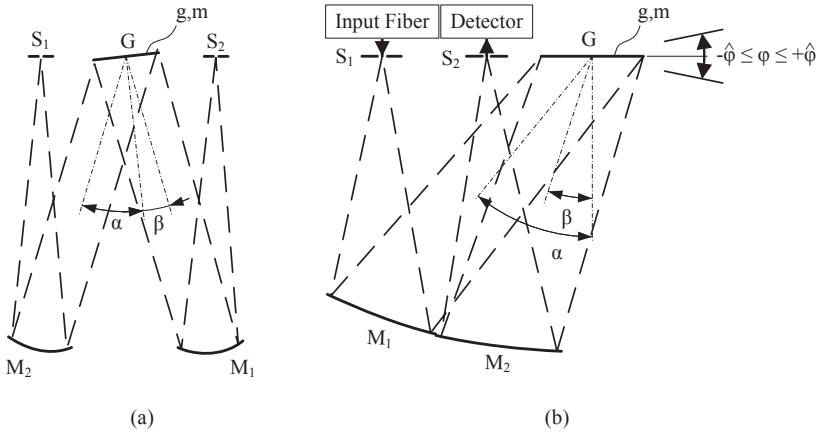


Figure 2.1: A Czerny-Turner monochromator illustrated in the historical, symmetrically arranged version (a) and a planar, unsymmetrical version (b) where the slits and the grating are located in a common plane. The planar version is well suited for a planar mounting approach. An input fiber and an integrated detector are part of this advanced system [13].

The basic grating equation gives the directions of constructive interference for light with the wavelength λ , that impinges on a grating with the grating constant g under the angle of incidence α and is diffracted in the m -th diffraction order under the angle of diffraction β . There are many publications that deal with different optical aspects, like the resolution and imaging properties of scanning grating spectrometers [14–19]. The major concern is the most favorable arrangement of the components for hybrid integration and planar mounting strategies. A suitable modification of the classical Czerny-Turner setup is needed, that allows for an assembly procedure, where all quasi-planar components are stacked on top of each other. In this way, the assembly can be done with modern pick and place die bonding machines. To find an appropriate concept the Czerny-Turner configuration is divided into three main parts. As can be seen in fig. 2.1 (a), the grating and the slits can be grouped together as the first part. The two mirrors are combined to the second part. Both are assembled with a spacer to adjust the correct focal length of the monochromator.

The basic idea is to integrate the group of grating and slits into one MEMS Substrate. This has several advantages. Thus, slits and their position relative to the grating and to each other can be controlled precisely. That means that some of the alignment procedures that are common practice in ordinary spectrometers are obsolete. They are replaced by lithographic pattern accuracy. However, one issue arises with the integration of the slits into the MEMS substrate. The result of a common substrate is an in plane configuration of the grating in rest position. In the classical Czerny-Turner spectrometer, the entrance and exit slit are located on opposite side of the grating. That is why in the originally Czerny-Turner setup illustrated in fig. 2.1 (a), the grating is tilted to yield different angles α and β . This difficulty can be overcome by placing both slits on the same side of the grating [16,20]. That implies that the two mirrors have to be positioned on one side of the grating, too. In this approach, illustrated in fig. 2.1 (b), the angles α and β are different due to the asymmetric arrangement of the slits. Therefore, the grating can be used in first diffraction order without any problem. This arrangement is appropriate for planar manufacturing and assembly. As far as optics substrates along with the two mirrors are concerned, modern manufacturing methods like single point diamond turning can be used to generate off-axis and highly unsymmetrical surfaces within one

piece of metal. An additional design constraint is that the grating plate moves symmetrically within $-\hat{\varphi} \leq \varphi \leq +\hat{\varphi}$, where φ is the detection angle. The substrate normal coincide with the rest position at $\varphi = 0^\circ$. All in all these restrictions lead to a limited solution space for the relevant design parameters λ , g , m and $\hat{\varphi}$. The reduced solution space simply arises from the fact, that the boundaries of the wavelength range at λ_{min} and λ_{max} are assumed to coincide with the detection amplitudes of the grating at $\pm\hat{\varphi}$. With the analytical expressions for the solution space derived by Puegner et. al. [21], the values of the design parameters for a certain spectral range, the NIR in the present case, have been determined. The grating properties are given by the technology available at Fraunhofer IPMS. A summary of the resulting specifications of the miniaturized scanning grating spectrometer are given in table 2.1.

Table 2.1: Characteristics of the miniaturized MEMS scanning grating spectrometer [13].

Parameter	Form	Typ	Unit
Grating constant	g	1600	nm
Diffraction order	m	-1	
Deviation angle	$ \hat{\varphi} $	9.5	$^\circ$
Spectral Range	$\Delta\lambda$	950	nm
Minimum Wavelength	λ_{min}	950	nm
Maximum Wavelength	λ_{max}	1900	nm
Spectral resolution	$d\lambda$	10	nm
Outer Dimensions	$L \times B \times H$	$15 \times 10 \times 14$	mm^3

The specifications of table 2.1 have been used as input for a first order optical system layout and a subsequent optic design process with commercially available optical design software. In order to minimize aberrations, the mirrors are designed as off-axis aspherical surface. The resulting optical path is illustrated in fig. 2.2 in a sectional representation.

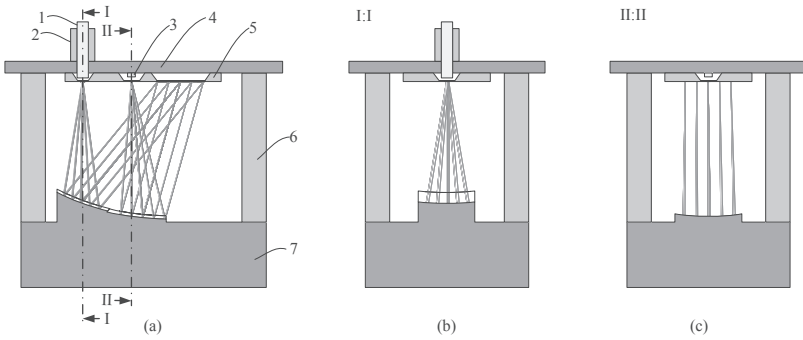


Figure 2.2: Sectional representations and optical path of the miniaturized scanning grating spectrometer for the near infrared between 950 nm and 1900 nm . The spectrometer consists of the following components: input fiber (1), ferrule (2), InGaAs photo detector (3), MEMS Grating with integrated slits (5), spacer (6) and optic substrate (7) containing two aspheric tilted mirrors. The whole set-up has a volume of $(15 \times 10 \times 14)\text{ mm}^3$ [13].

3 Spectrometer realization

According to fig. 2.2 the miniaturized MEMS scanning grating spectrometer consists of seven separate parts which are arranged as a stack. The individual components are made of different materials applying special technologies. The first one makes use of semiconductor technologies and is employed for the MEMS device. The second is the fabrication of metallic parts by machining, especially single point diamond turning for the optical substrate with its mirrors. In order to illustrate the arrangement of the parts inside the spectrometer and clarify the planar stacked mounting, fig. 2.3 illustrates two exploded views of 3-d CAD model.

The printed circuit board serving as carrier substrate has a size of $(17 \times 12)\text{ mm}^2$. The gold metalization is suited for wire bonding and conductive adhesive bonding, as well. On top of the carrier substrate the InGaAs photo diode with the physical dimensions of about $(0.49 \times 0.49 \times 0.2)\text{ mm}^3$ is mounted. The photo diode has a spectral range of 900 nm to 1900 nm with a peak sensitivity at 1750 nm . In the

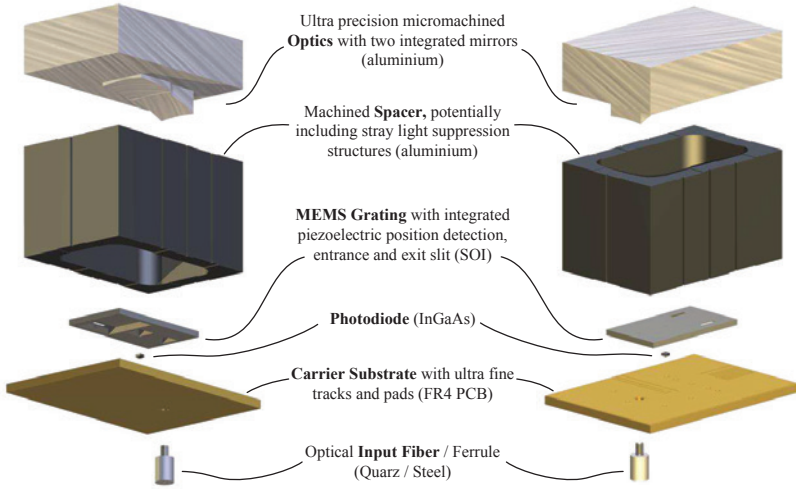


Figure 2.3: Exploded views from bottom to top (a) and from top to bottom (b) of the miniaturized scanning grating spectrometer. The ultra precision machined optical substrate and machined spacer of the prototype made from aluminum can be replaced by plastic parts, microinjection embossing or shiny pressing, respectively [13].

next step, the MEMS device is mounted to the PCB and electrically connected by wire bonding. It is positioned in such a way, that the photo diode previously bonded to the same PCB is enclosed in one of two cavities that defines the exit slit. The MEMS grating, which is the key component of the miniaturized spectrometer, contains a 1-d scanning trapezoidal grating with grating constant of $g = 1600 \text{ nm}$ and a size of $(3 \times 3) \text{ mm}^2$ [22, 23]. The MEMS chip $(9.6 \times 5.3) \text{ mm}^2$ wide not only carries the rotatable grating plate, but also features a piezoresistive position detectors and the two optical slits. Fabrication and test of the MEMS device were performed in the IPMS clean room facility on 6" silicon on insulator (SOI) substrates. For better stray light suppression, the spacer with dimensions of $(15 \times 10 \times 9.1) \text{ mm}^3$ is black anodized. The spacer is mounted on the optics substrate by the same conductive adhesive used in the previous assembly steps. Although electrical con-

ductivity is not necessary at this point, the thermal conductivity of the applied adhesive might be advantageous. Optics (a), spacer (b) and the corresponding subassembly (c) are illustrated in fig. 2.4.

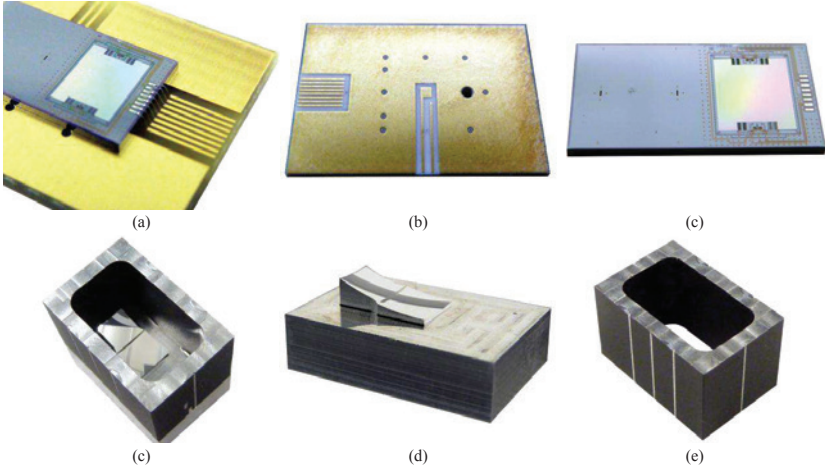


Figure 2.4: The lower subassembly (a) consisting of carrier substrate (b), MEMS device (c) and buried InGaAs photo detector as well as the upper subassembly consisting of ultra precision-machined optics substrate (d) and precision milled spacer (e) are the component parts of miniaturized MEMS scanning grating spectrometer [13].

Finally, the upper and the lower subassemblies are joined together by adhesive bonding. The assembly process is completed by mounting the optical fiber to the carrier substrate. To this end, the ferrule of the fiber is inserted into the carrier substrate from the backside through a matching hole. Afterwards the polished surface of the fiber is located in close proximity the entrance slit. The second end of the fiber is customized with a SMA fiber connector. The alignment and assembly of whole system is performed by a fully automated micro assembly production platform. An illustration of the complete MEMS spectrometer is shown in fig 2.5.

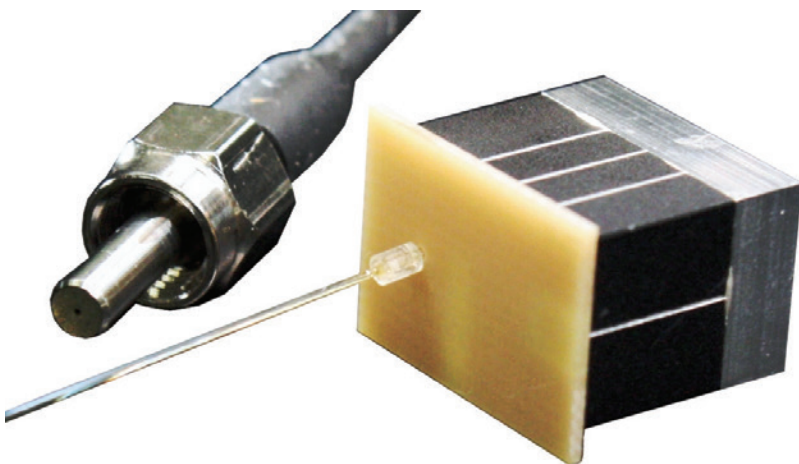


Figure 2.5: Hybrid-integrated MEMS scanning grating spectrometer for the near infrared between 950 nm and 1900 nm with a volume of only $(15 \times 10 \times 14)\text{ mm}^3$. The spectrometer is nearly as small as the corresponding SMA fiber connector [13].

4 Measurement results

The hybrid-integrated spectrometer has been connected to a system electronic for readout and drive. This board is controlled by a digital platform that computes final spectra by unfolding the sinusoidal movement of the grating and transfers data as a table of measured intensities for well-defined wavelength to the host computer. The complete spectroscopic measurement system consisting of microspectrometer and the corresponding electronic is illustrated in fig. 2.6. On the host computer spectral evaluation software was implemented for the scanning grating spectrometer SGS 1900. The digital platform of the hybrid-integrated spectrometer has been realized in a way, that the application software remains compatible. Thus, applications served before can easily be transferred to the hybrid spectrometer system. Examples for materials analysis have been evaluated in different context. For recycling issues, the selection of different kinds of plastics has been demonstrated. Pharmaceutical products were analyzed and different examples

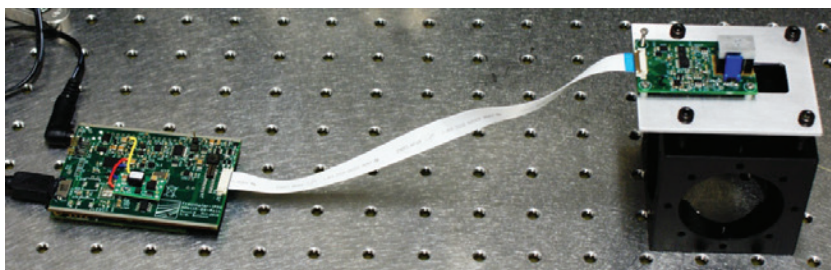


Figure 2.6: The complete USB-powered miniaturized spectroscopic measurement system consisting of microspectrometer and the corresponding electronic [24].

in the area of food analysis have been considered. The water content and the sugar matrix (glucose, fructose, sucrose) of honey samples were analyzed quantitatively. For the water-ethanol system, a chemometric model was implemented based on synthetic mixtures. Using this model the alcohol content of spirits could be measured. A demo setup used for the presentation of the scanning grating spectrometer SGS 1900 is illustrated in fig. 2.7.

5 Discussion and summary

The miniaturization of scanning grating spectrometer has been a challenging task. The Czerny-Turner setup has been found a particularly suitable starting point for miniaturization. The reduction of system dimensions affects all the major parts of a spectrometer. The MEMS scanning grating developed at Fraunhofer IPMS is a small robust device, which might enable the use of spectrometers in harsh environments. The integration of entrance and exit slit into the MEMS chip leads to a significant reduction of the spectrometers outline. In addition, the numbers of components that have to be adjusted in the spectrometer is reduced. The use of aspheric, off-axis surfaces for the collimating and focusing mirror, fabricated by single point diamond turning, ensures good optical system performance. Due to the small size of components and their asymmetrical shape, some manufacturing tolerances are rather tight. Modern die bonding machines can provide the means

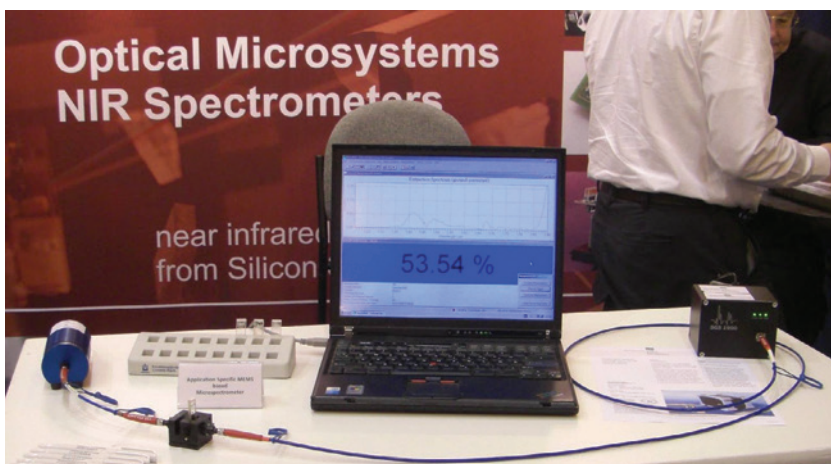


Figure 2.7: Exemplary demo setup used for the presentation of the scanning grating spectrometer SGS 1900. The measurement result displayed on the screen is the alcohol concentrations liquid sample.

for highly accurate fully automated assembly processes needed. Today the first prototype is working already but the aims for the spectrometer resolution have not yet been met. First simple applications could be served even with the limited performance but more sophisticated examples requiring the same optical performance that has been achieved for the larger SGS 1900 scanning grating spectrometer. Active assembly is the next step planned to increase accuracy during the realization of the hybrid-integrated spectrometer. Achieving the resolution the spectrometer was design for, interesting applications in the field of food analysis or medical will be addressed.

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