Development of a compact NIR sensor using MEMS-FPI NIR spectral detectors

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Abstract

The subject of this paper is the design and development of a miniaturized NIR spectral sensor using MEMS-FPI NIR spectral detectors. Devices fabricated by the MEMS process allow the integration of mechanical components within a very limited package space. By using multiple MEMS-FPI NIR spectral detectors fabricated by this process, a very compact and equally cost-effective NIR spectral sensor can be developed, which can be used in various fields such as industrial manufacturing and processing, among others. In this paper focusing on the sensor concept, the NIR spectral sensor consisting of several spectral detectors, the signal processing as well as the control and pre-processing of the recorded NIR spectra by a microcontroller is explained in detail. In addition, the software unit is presented, which is connected to the sensor via an interface and takes over the control and evaluation of the measured spectra. To demonstrate the functionality of the sensor, an insight into multiple spectral measurements performed is given. The developed sensor is, by the integration of several MEMS-FPI spectral detectors, an innovative approach of a compact NIR spectral sensor.

1 Introduction

Spectroscopy describes a group of analytical methods used in chemistry and physics. Here, radiation is decomposed according to different properties such as wavelength or energy and mass. The intensity distribution, which results after the decomposition, is called spectrum and can be examined afterwards by different procedures (mostly statistically). The intensity spectrum can be used to draw conclusions about the properties of the radiation source or the medium through which the radiation has passed.
One subfield of spectroscopy is near-infrared (NIR) spectroscopy. Here, the sample to be analyzed is irradiated with a radiation source and the transmitted radiation is recorded after passing through the sample. The most common method is transmission, but reflection is also possible. Due to the simplified and partly unnecessary sample preparation, NIR spectroscopy has significant advantages over other analytical methods. For this reason, especially in recent years, NIR spectroscopy has increasingly been applied in the producing and processing industries: they range from agriculture, the feed and food industry, to process control in various branches of industry, to sorting in recycling plants [1,2,3].
The spectrometers used for recording spectrograms in the NIR range mostly work according to the principle of dispersion. Here, the radiation transmitted by the sample is split into its spectral ranges (e.g. by using prisms) and then recorded. Another way of recording NIR spectra is the use of interferometers. Interferometers make use of the resonance properties by superimposing the beams and thus generate an interferogram, which can be converted into a spectrogram.
The aim of the sensor concept presented here is to introduce a compact as well as highly integrated NIR spectral sensor using several MEMS-FPI (Fabry-Pérot Interferometer) NIR spectral detectors. A total of three spectral detectors are used, which together can record a spectral range from 1350 nm to 2150 nm. All detectors are integrated into one sensor head. A microcontroller, which is part of the sensor concept, controls the electronic components within the sensor and also enables communication with a host system. This host system controls the sensor and performs the computationally intensive analysis and evaluation of the recorded NIR spectra.
In this paper, first a brief insight into the current state of the art of compact NIR spectral sensors is given. This is followed by a presentation of the sensor concept. The complete functionality of the hardware and software of the sensor is presented in detail. Then, measurements with the sensor are shown and their results are discussed. The paper concludes with a summary and an outlook.

2 State of the art

There are several compact NIR sensors out on the market, some of which differ greatly in their properties and configurations. For example, the NIR sensor NIRscan [4] developed by Texas Instrument uses digital micromirror devices (DMD) to achieve spectral decomposition according to

wavelength. A detector array is used to record the spectrum. Subsequently, the acquired data can be transferred via a USB or Bluetooth connection for further processing.
The manufacturer Spectral Engines sells several compact NIR spectral sensors [5]. A set of spectral sensors consists of five individual sensors that can detect different wavelength ranges of NIR radiation. Each individual sensor unit has a MEMS-FPI NIR spectral detector and corresponding signal processing including a USB interface.
In a paper by Artem Ivanov from the University of Landshut, a sensor solution is presented that explains the design and function of a NIR sensor based on a MEMS-FPI NIR spectral detector [7]. As in the present paper, a spectral detector from Hamamatsu Photonics is used for this purpose. The knowledge gained was taken into account in the design and development of the integrated NIR spectral sensor and optimized where necessary.
The paper "Principles and Applications of Miniaturized Near-Infrared (NIR) Spectrometers" (2021) provides a good overview of currently available miniaturized NIR spectrometers and their application areas [8].

3 Presentation of the system concept

The NIR sensor system presented in this paper uses multiple MEMS-FPI NIR spectral detectors to perform a spectral measurement over a wavelength range from 1350 nm to 2150 nm. **Figure 1** shows the designed sensor. The sensor is cylindrical in shape and has a diameter of 50 mm with a height of approximately 60 mm. The physical operation is based on the principle of reflection. The object to be examined is placed in front of the sensor head and irradiated by the integrated NIR radiation sources. The radiation hits the object, is reflected by it (diffusely) and is directed towards several NIR spectral detectors, which record the intensity. A protective glass is placed on the sensor head, to protect the detectors from external influences such as moisture and dirt. Thus, it is possible to examine solid as well as liquid samples. The chosen design also makes integration into process chains mechanically relatively easy.
The sensor is operated with a voltage of 12 V and has a USB and CAN interface for communication with a host system for industrial coupling. **Figure 2** shows the principle diagram of the NIR sensor components and their signal flow. According to the figure, the structure of the sensor system can be divided into three areas: the sensor head, the signal processing area and the sensor controller. In the following subchapters, an insight into these three areas will be given and their functionality and interaction will be clarified. Another part of the sensor concept is the software control and evaluation of the measured NIR spectra, which will be discussed in the last subchapter. The implementation of the communication between the NIR sensor and the host system is explained and an insight into the developed software, which can be executed on an embedded system or PC as a host system to control the sensor, is given.

3.1 The sensor head

The sensor head of the NIR spectral sensor realizes the physical coupling to the sample under investigation. Three radiation sources are used here together with three MEMS-FPI spectral detectors arranged in a circle (cf. **Figure 2**). The radiation sources used for the emission of NIR radiation are miniature light sources. These are characterized by a very broadband radiation spectrum. These sources are controlled by an adjustable current source. The current of the radiation sources can be continuously adjusted by the current source and thus influence the radiation intensity of the sources. Thus, in contrast to controlling the sources by means of a PWM signal, it is not necessary to ensure synchronous control of the radiation sources together with the scanning of the photodiodes used. In addition, analog control of the sources has the advantage that no high-frequency interference signals are generated which could have a negative influence on the signal processing area.
The radiation emitted by the radiation sources hits the sample under investigation, is reflected and hits the MEMS-FPI NIR spectral detector, which record the spectrum. Three spectral detectors [9] from the manufacturer Hamamatsu Photonics perform this task, which differ in their sensitive spectral ranges. The spectral detectors are manufactured using the MEMS fabrication process and consist of three relevant components, which are housed in a compact TO-5 package. **Figure 3** shows the structure of the detector and illustrates its operation. The incident radiation impacting on the detector first passes through an optical bandpass filter. Only the spectral range relevant to the detector passes through the filter. The radiation then hits the

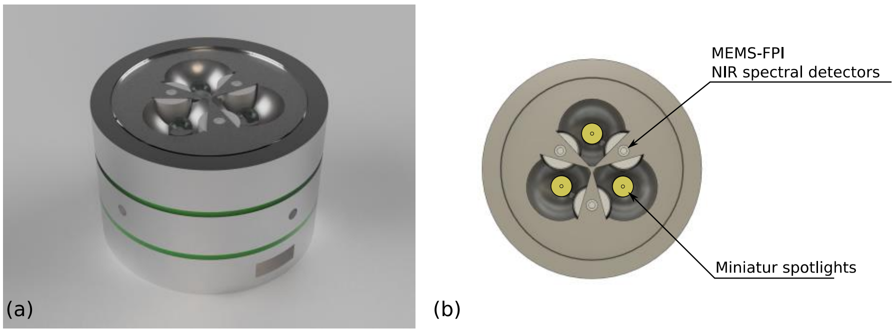

Figure 1 Image of the developed NIR spectral sensor (a), top view of the sensor head (b).

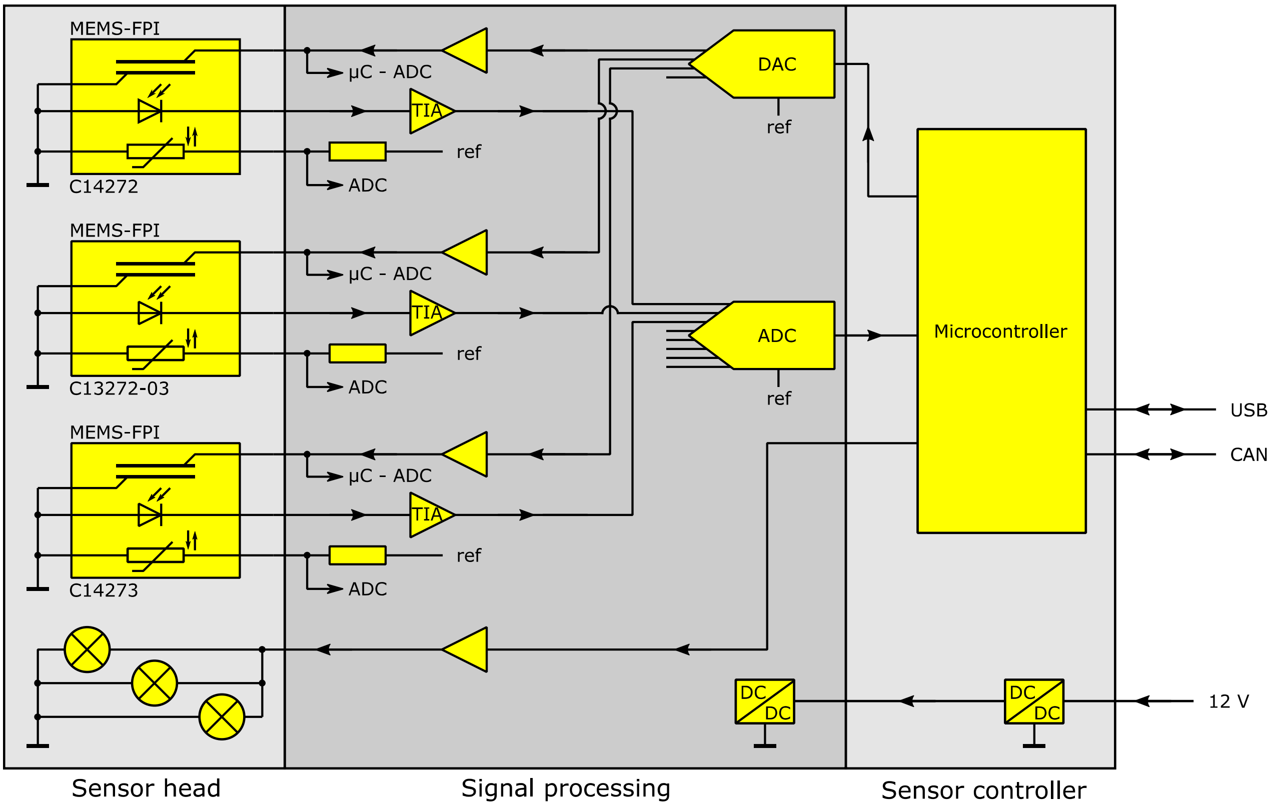

Figure 2 Schematic diagram of the electronics of the NIR spectral sensor divided into the three areas: sensor head, signal processing and sensor controller.

MEMS-FPI element. This consists of two semi-transparent mirrors facing each other, the distance between which can be varied. Radiation passes through one of the mirrors and is afterwards reflected between the two mirrors. Depending on the distance between the mirrors, resonance occurs for a certain wavelength, causing constructive interference of just that wavelength. Other spectral ranges are almost completely cancelled out by destructive interference. The thus amplified wavelength is transmitted through the second mirror and hits an InGaAs photodiode. The photodiode generates a current proportional to the radiation intensity, which can then be further processed or evaluated.

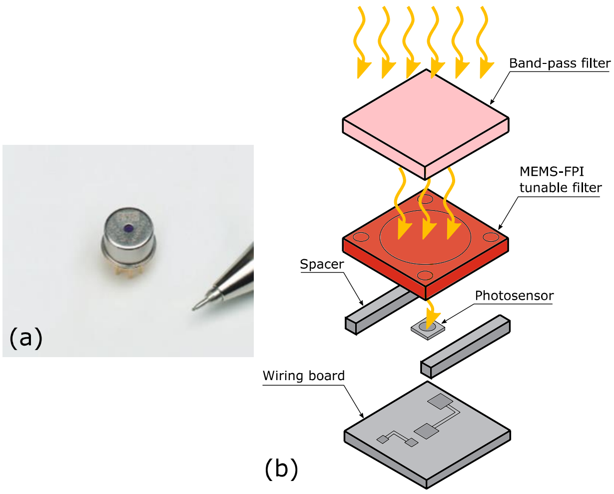

Figure 3 Photo (a) and operating principle (b) of the Hamamatsu MEMS-FPI NIR spectral detector [10].

As described above, in this mode of operation the FPI element is not operated like a typical interferometer, but fulfills its function as an optical filter which filters the incoming radiation according to a certain wavelength. The mirror spacing of the FPI element can be varied by applying a voltage. Both mirrors are connected to an electrical potential. An applied voltage causes an electric field between the mirrors whose strength is proportional to the potential difference; the larger the potential difference, the stronger the electric field. Since one of the mirrors is loosely supported, the force applied to it causes the mirror to move in the direction of the other mirror. The control of the MEMS-FPI spectral detector is described in chapter 3.2.
If this control voltage, which sets the FPI element, is continuously changed, the complete spectral range of the detector can be continuously detected. A great advantage of these detectors is that the complete spectrum does not necessarily have to be detected. Thus, it is conceivable that only ranges or even individual intensity values of the spectrum can be filtered and measured. This selective and conditional acquisition of spectral regions can significantly reduce the duration of a measurement (typ. 1.5 s for a complete spectrum). Furthermore, it offers the possibility to develop new and innovative algorithms, which realize an analysis of the sample starting from a reduced NIR spectrum. Chapter 4 gives an insight into the processing and evaluation of the measured spectra.
Hamamatsu offers four types of MEMS-FPI NIR spectral detectors, which differ mainly in the sensitive spectral

range. **Table 1** provides an overview of the available spectral detectors and their spectral ranges. By integrating the three detectors C14272, C13272-03 and C14273 into one sensor head, a spectral range from 1350 nm to 2150 nm can be detected.

Table 1 Available MEMS-FPI NIR detectors made by Hamamatsu.

Type no.	**Spectral response range**	**Spectral resolution (FWHM) Max.**	**Photosensitive area**
C14272	1350 - 1650 nm	18 nm	0.3 mm
C13272-02	1550 - 1850 nm	20 nm	0.1 mm
C13272-03	1550 - 1850 nm	20 nm	0.3 mm
C14273	1750 - 2150 nm	22 nm	0.3 mm

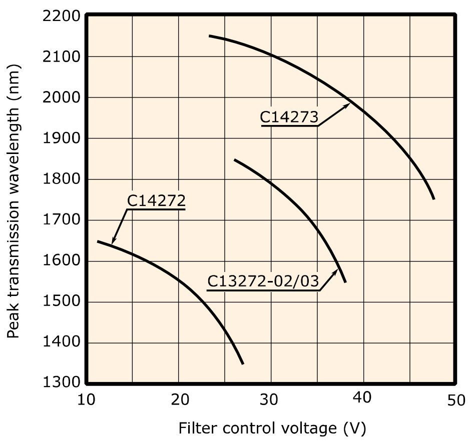

Figure 4 Typical dependence between control voltage and transmission wavelength of the FPI elements [10].

Apart from the optical elements, the spectral detectors each have a thermistor (NTC). By measuring the resistance value, the temperature of the detector can be monitored, which has an influence on the FPI element. A change in temperature causes a resonance shift which distorts the spectral measurement. This shift is different for the three detectors and amounts to approx. 0.3 nm/K. To counteract this, the control voltage of the FPI elements must be adjusted according to the temperature, which is done by feeding back the temperature to the sensor controller.

3.2 The signal processing

The signal processing area provides the interface between the analog signals of the spectral detector and the digital microcontroller unit. The signal processing can be divided into two main areas. On the one hand, a control voltage must be implemented to drive the FPI elements of the spectral detectors. On the other hand, the analog photodiode currents of the photodiodes must be converted into a digital signal in order to be able to evaluate them.

A 4-channel digital-to-analog converter (DAC) is used to provide the control voltage for the three spectral detectors. This converter is connected to the microcontroller via an SPI interface and is characterized by very low-noise behavior. The four channels have a resolution of 16 bits. The FPI elements of the three spectral detectors used require different voltages for adjustment. **Figure 4** shows the typical relationship between applied voltage and transmitted wavelength. It can be seen that as the voltage increases, the wavelength of the transmitted signal decreases. According to Hamamatsu, if the applied voltage exceeds the maximum voltage value by about 0.5 V, the so-called pull-in effect occurs: the mirrors collide with each other and may no longer be able to be separated; this leads to irreparable damage to the FPI element. The actual dependence between voltage and transmitted wavelength varies for each detector and must be determined by calibration before use. The manufacturer calibrates each detector once and records the relationship.

As can be seen in **Figure 4** the maximum control voltage is approx. 48 V for the C14273 detector. To achieve this (powerless) voltage, an integrated oscillating circuit is used to generate a voltage of 50 V from the 12 V operating voltage. The three output signals of the DAC are each connected to an operational amplifier. The non-inverted operational amplifiers operate with a unipolar voltage and amplify the output signals of the DAC for the FPI elements.

The current generated by the photodiode is processed in two steps. First, a transimpedance amplifier (TIA) is used to generate a proportional voltage from the current. By using a reference voltage source that steps up the current with an offset, the most linear amplification possible can be achieved.

To convert the voltage signals of the photodiodes into a digital signal, a 16-bit analog-to-digital converter (ADC) is used. This has 8 inputs. Thus, the output voltages of the three transimpedance amplifiers can be read in. Also, the voltage drop across the thermistors can be determined and thus their resistance values or their temperatures can be concluded. The ADC has an SPI interface for communication and a reference voltage source to guarantee a low-noise conversion of the voltage signals.

3.3 The sensor controller

The sensor controller takes over the control of the electronic components of the spectral sensor, the preprocessing of the spectral data and the communication with a host system. The microcontroller used in the sensor is based on the ARM Cortex M4 architecture. It has several SPI interfaces as well as integrated communication units to use the USB or CAN protocol. There are also several inputs and outputs to work with analog signals, which is used, among other things, to read in the voltages of the FPI elements (via a voltage divider) and thus monitor them.

The sensor controller has a USB and CAN interface to communicate with a host system. The USB interface allows the sensor to be controlled in a laboratory environment via a serial interface. The CAN interface, on the other hand, is intended for use in an industrial environment, where CAN is a common and widely used communication protocol within process chains. Both communication modes can be used to configure the sensor and to transmit

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the recorded spectra to the host system. Due to the limited performance of the microcontroller, there is no evaluation of the spectra on the sensor; only smoothing of the spectra by averaging is realized to keep the data transfer as low as possible.

When the NIR sensor receives the command to measure, the microcontroller performs several steps. According to the wavelength to be measured, the microcontroller uses a lookup table (LUT) to determine the necessary voltage to set the FPI elements. These voltages are set using the DAC and amplifiers. After that follows a waiting time of 3 ms. This time is needed by the FPI elements to reach a stable state. After this time has elapsed, the intensity of the NIR radiation is read in via the photodiode current using the ADC. Subsequently, by setting a new control voltage of the FPI element, another wavelength is detected and the procedure starts again. To minimize interference as well as noise of the photodiode current, the intensity is measured and averaged several times in succession. A further option is to repeat the recording of a spectrum several times and to average over the measured spectra. The reproducibility of the FPI elements is given by Hamamatsu as ± 2 nm. The averaging of the spectra or the intensity values takes place on the microcontroller, which then transmits the spectra to the host system via the external interface.

3.4 The software

A graphical user interface was developed for the use of the NIR sensor. On the one hand, the software allows the control of the sensor via a USB interface as well as the analysis and evaluation of the measured spectra. **Figure 5** shows a screenshot of the sensor control area. A wide variety of sensor parameters can be set and adjusted. For example, the wavelengths to be scanned can be configured and the number of measurements for averaging can be selected individually. Spectra can be measured once or continuously via the software. The current status of the sensor is displayed on the user interface. The measured spectrum can be viewed directly in the software to get a first impression of the measurement. Various functions such as saving and exporting are also possible.

The evaluation and analysis of the measured spectra can be done by different methods. The developed software therefor provides various possibilities. The spectra can be analyzed directly during the measurement process or afterwards. Different regression models are available, which allow an analysis of the spectra based on classical chemometrics by a multivariate calibration. The calibration models required for this can be loaded from a database.

The software also allows the implementation of individual algorithms for the analysis of the measured spectra. For this purpose, it is possible to create individual functions in Python programming language, which can be integrated via a provided software interface. These functions determine then, on basis of the spectrum, the analysis value concerned. In this way, machine learning approaches, among others, can be tested efficiently and quickly. By incorporating different libraries such as TensorFlow or PyTorch, the range of functions and analyses can be expanded considerably. For example, the analysis of recorded spectra with neural networks is being investigated in current studies.

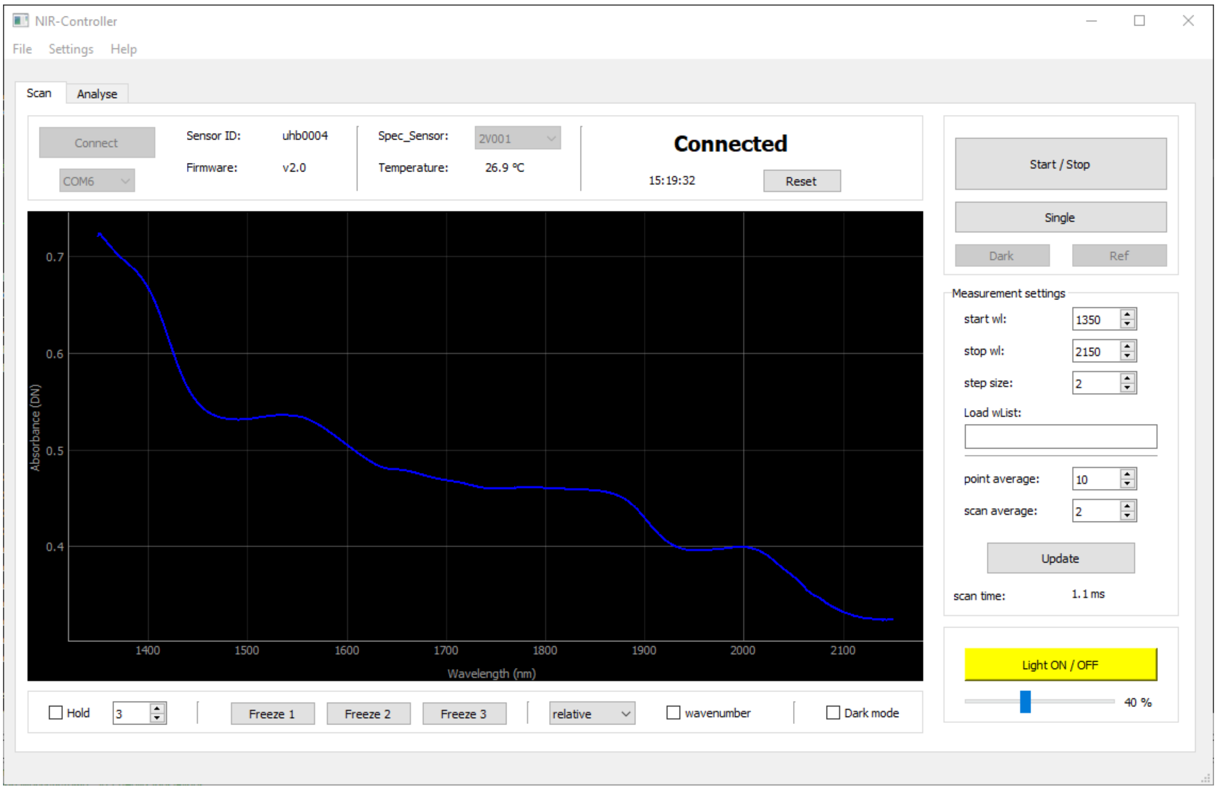

Figure 5 Screenshot of the software for sensor control and evaluation of spectral data.

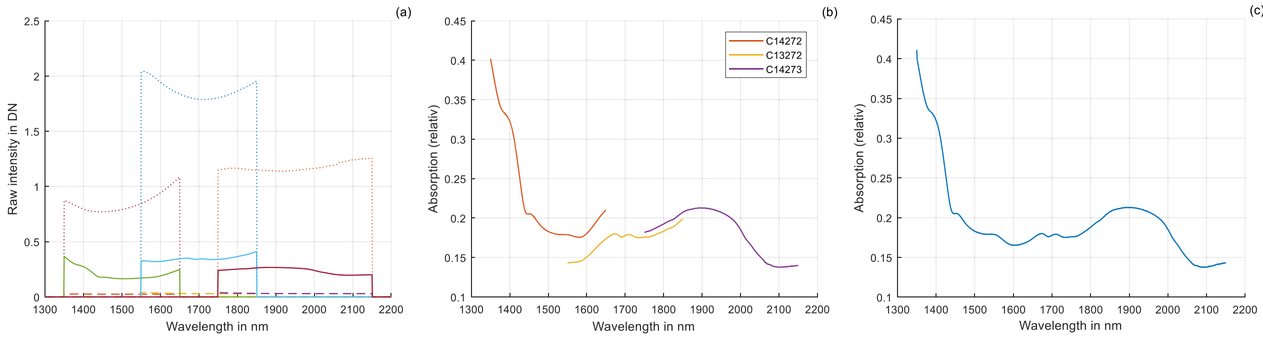

Figure 6 Different representations of a spectrum measurement. Raw data (solid line) of the sensor with reference spectra (a), calibration of the partial spectra by the reference spectra (b), fusion of the partial spectra to a spectrum by a weighted sine interpolation (c).

4 Measurements and discussion

When starting a measurement with the NIR sensor, the different wavelengths per detector are set one after the other and the radiation intensities are determined via the photodiode. The measurement process is carried out simultaneously with the three NIR detectors, which significantly reduces the time required to record a spectrum. Thus, approximately 5 ms are required per wavelength to measure the intensity. This time is needed to reach a mechanically as well as electrically stable state. Thus, a time of approximately 1.5 s is required per detector to detect the complete wavelength range (300 nm wavelength range with 1 nm increment scanning). By measuring simultaneously, a spectral range of 800 nm (1350 – 2150 mn) can thus be achieved in the same time. By selectively measuring individual spectral ranges or even only individual intensity values, the spectrum and thus the measurement time can also be significantly reduced. The intensity measurements do not necessarily have to be evenly distributed over the spectrum. It is therefore possible to measure individual interesting wavenumbers or wavelength ranges in the spectrum.
In order to be able to evaluate a recorded spectrum, a spectrum calibration must first be carried out. For this purpose, a dark and reference measurement is performed with the sensor at the beginning of a measurement series. These determined spectra are used as reference spectra for the further measurements and are calculated with these to an absorption spectrum.

Since the NIR sensor has three spectral detectors, three spectra are measured accordingly. **Figure 6** shows exemplary the raw spectra of a spectral measurement (a) as well as the corresponding absorption spectra after the spectral calibration (b). Three separate spectral regions can be seen, which partially overlap. It can also be seen that the three partial spectra show an approximately continuous course, with an offset in the overlapping areas. In order to generate a coherent spectrum from the partial spectra, various approaches are currently being investigated. Moreover, **Figure 6** shows an example of the fusion of the partial spectra using a weighted sine interpolation (c).
Figure 7 shows measurements of various samples. All spectra were recorded uniformly over the complete wavelength range with a scan increment of 2 nm. Each spectrum was recorded a total of four times and 10 intensity values per wavelength were recorded per scan. Subsequently, all intensity values per wavelength were averaged to smooth the generated spectra.
The samples are different fine granular foods. These were filled into cuvettes and extraneous light was excluded by a lid. It can be seen that the spectra are visibly different from each other. The filling height of the samples was chosen so that no radiation from the sources would pass through the samples. This is crucial, especially for thin materials, because otherwise radiation energy is lost. In these cases it is useful to place a reference material behind the samples to reflect radiation transmitted through the sample. In the case of transparent liquids, a so-called reference stamp is often used to reduce the filling height to less than one millimeter.

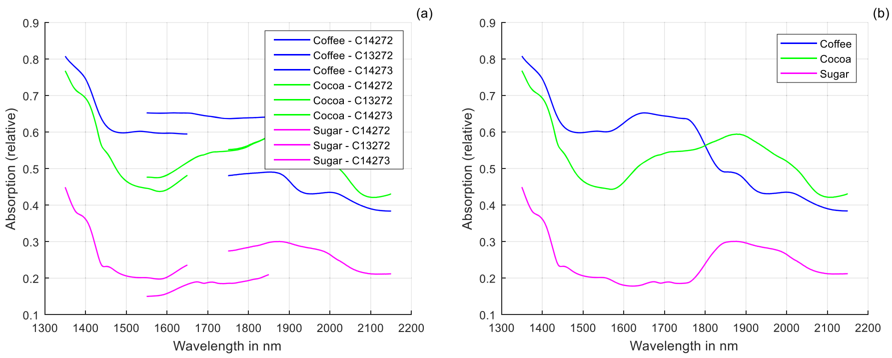

Figure 7 Spectral measurements of different powdered samples. Representation of the individual partial spectra (a), fusion of the partial spectra (b).

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Since this is a mixture of reflected and transmitted radiation, it is referred to as transflection.
Measurements at different temperatures have shown that the implemented temperature compensation stabilizes the FPI element. Thus, the miniature spotlights cause the detectors to heat up to 55 °C. This heating results in a shift of the resonance frequency of about - 10 nm (reduction of the transmitted resonance frequency), which will be avoided by the compensation. For test purposes, a narrowband NIR signal was emitted with an LED and this was recorded with the NIR sensor. Repeated measurements showed a standard deviation of the wavelength stability of about ± 1 nm at constant temperature.
There is still room for improvement in the control of the FPI control voltage. At the present time, there is no feedback of the output amplified control voltage in its calculation. This should still be implemented to obtain reliability and stability of the set wavelength and to avoid drifting away of the voltage. Under laboratory conditions with a stabilized power supply as voltage source, no noise in the form of ripple could be detected on the control voltages. Thus, it can be assumed that the stability of the wavelength is dominated by the detector with a reproducibility of ± 2 nm in terms of hardware.
Besides the stability and reliability of the FPI element, the resolving power of the photodiode is an essential characteristic of the sensor. The photodiodes have a wavenumber-dependent resolution of approximately 9 to 16 nm (FWHM) at an optical aperture of 0.09. Measurements have shown that the standard deviation of the intensity values is in the range of up to 0.01 %. In addition, it was found that the standard deviation increases towards the edges of the detectable spectral regions.
As several detectors are used during spectral investigations of inhomogeneous samples, it is a problem that different areas are examined by these. Because each detector looks at a different section of the sample, the current solution requires homogeneity of the sample. A solution for this problem would be the optical detection of only one section and the distribution to the three detectors.
For the evaluation and analysis of the measured spectra, different approaches are pursued, which are still part of current research work. Analyses with rather classical chemometric methods, such as a partial least squares regression (PLS), have performed rather poorly in this regard. For this reason, the focus in the development of analysis algorithms is on the area of machine learning. For example, the analysis of spectral measurements with artificial neural networks or a random forest yielded positive results, which still need to be investigated in further steps.

5 Summary and outlook

The integration of multiple MEMS-FPI NIR spectral detectors into one sensor head represents an interesting and novel approach to the acquisition of NIR spectra. Thus, it is possible to take advantage of MEMS-FPI spectral detectors over an extended spectral range.
The presented NIR sensor includes three MEMS-FPI spectral detectors that can record a spectral range from 1350 nm to 2150 nm. NIR radiation is emitted by multiple broadband radiation sources, then it is reflected (diffusely) from the sample and impinges on the spectral detectors. By using the FPI elements as optical filters, the intensity of the radiation can be selectively recorded across the wavelength. Integrated circuits for signal processing, control and pre-processing of the spectral data enable synchronous spectrum measurement. For integration into laboratory or process chains, the sensor has a USB as well as CAN interface. The NIR sensor can be controlled and configured for measurement via a graphical software interface. In addition, recorded spectra can be evaluated and analyzed directly. For this purpose, various functions from the field of classical chemometrics are available as well as the possibility to integrate individual functions for analysis. In particular, approaches from the field of machine learning can be investigated for spectral analysis.
The NIR sensor presented offers the potential for cost reduction compared to conventional solutions for use in the laboratory or industrial manufacturing and processing.
Several approaches are currently being pursued to optimize and further develop the NIR sensor. For example, the influence of different radiation sources and optics is being investigated in terms of hardware technology in order to be able to use more efficient sources. In addition, continuous enhancements to the sensor software are taking place to test additional analysis algorithms and expand the range of functions. An essential part of this work is the investigation of analysis algorithms based on a reduced NIR spectrum. For this purpose, only selected spectral regions are to be recorded with the help of the sensor and algorithms are to provide sufficiently accurate analysis results compared to a complete spectrum. In this context, the use of machine learning algorithms is considered in particular. In order to investigate the use of sensor technology in an industrial environment, measurements in process chains are planned.

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