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Investigation of Application-Specific Assembly Technologies and Metrological Influencing Factors of MEMS-based NIR Spectral Sensors

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Abstract

The article compares different construction and housing technologies of a compact, MEMS-based near-infrared (NIR) spectral sensor and highlights their advantages and disadvantages. The arrangement and alignment of the radiation source and the detector in particular have a significant influence on the quality of the spectral measurement. The optical beam path can be positively influenced by the design of these sensor components, thus improving the spectral measurements. In addition, external mechanical and thermal influencing factors on MEMS spectral detectors are examined and possibilities for algorithmic calibration and compensation are presented. Mechanical vibrations and shocks influence the interferometer in the MEMS-FPI detector, which results in a disturbance of the measurement. Thermal loads, such as temperature fluctuations, also lead to a change in the measurement behavior. This results in a measurement deviation of the detected intensity and wavelength. The concepts and results presented serve as a basis for taking the development of new types of MEMS-based spectral sensors to a new level and promoting their applicability in various areas.

Keywords: Optical measurement methods, near-infrared spectroscopy, MEMS sensor technology, sensor design

Introduction

Near-infrared spectroscopy (NIRS) is a physical analysis method that has numerous advantages over other methods, such as non-invasive, contactless measurement and the possibility of direct evaluation. Due to these positive characteristics, an increased use of NIRS in the industrial environment can be observed, especially in recent years. Companies are showing increasing interest in using NIR sensors in various areas such as agriculture, food and animal feed production and the recycling industry [1, 2]. There are also efforts to establish NIRS in areas of process engineering for monitoring different process parameters (such as cooling lubricants [3]) by means of inline or online measurement. However, due to the special requirements in an industrial context, conventional NIR spectrometers, which were originally developed for laboratory use, are unsuitable for these application environments. This requires the use of new types of measuring systems that can cope with the diverse requirements of industrial and process environments.

The challenge

The realization of promising measurement systems is made possible by the use of MEMS-based (microelectromechanical system) spectral detectors. These detectors have a miniaturized design and thus enable the conception of a compact measuring system [4]. These measuring systems can thus be adapted, configured and optimized according to the application-specific requirements in the industrial sector. However, these detectors and measuring systems have typical and characteristic features and restrictions that must be taken into account when designing and evaluating the measuring system and the measurement results. In particular, the accurate and reliable measurement of the NIR spectrum poses a challenge in harsh industrial environments. In this context, the article will present various application-specific design and housing technologies as well as the challenges posed by coupled mechanical interference and thermal influences.

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MEMS-FPI spectral detectors

The focus of the investigations is on the use of MEMS-FPI (Fabry-Pérot interferometer) NIR detectors. MEMS-FPI spectral detectors, as shown in Fig. 1, essentially consist of three components: optical bandpass filter, FPI element and photosensor. The FPI element, which consists of two semi-transparent mirrors (reflectors), transmits a specific wavelength by varying the distance between the two mirrors, which then hits the photosensor. The FPI element thus acts as an optical resonator, which enables selective measurement of discrete intensity values of the spectrum. By continuously varying the distance, a quasi-continuous spectrum can be measured.

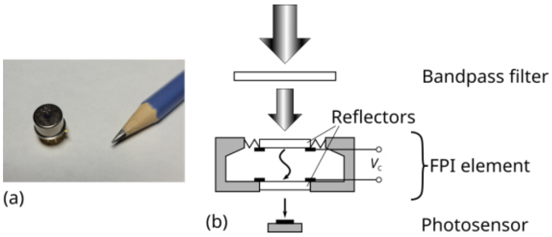

Fig. 1: Image (a) and functional principle (b) of a MEMS-FPI detector

However, due to their design and properties, MEMS-FPI spectral detectors are sensitive to various external factors. Mechanical and thermal influences in particular can cause an unintentional and sometimes unpredictable shift (modulation) of the mirrors, which has an impact on the spectral measurement.

Housing technologies

The conception, development and design of a MEMS-based NIR spectral sensor for use in an industrial environment involves diverse requirements. For example, the sensor should be as adaptive and modular as possible in order to meet the application-specific requirements and enable integration into different process environments. The sensor presented in [5] forms the basis for the design and housing concept. The presented sensor includes three MEMS-FPI NIR spectral detectors, which makes it possible to measure a spectrum in the wavelength range from 1350 nm to 2150 nm. Since a single detector only has a limited spectral sensitivity of a window of approx. 300 nm, a large part of the NIR spectrum can be captured by integrating several detectors into one sensor head.

As can be seen in Figure 2, the detectors are arranged in a circle and alternate with radiation sources. Miniaturized tungsten lamps are used as radiation sources, which generate a broadband emission spectrum.

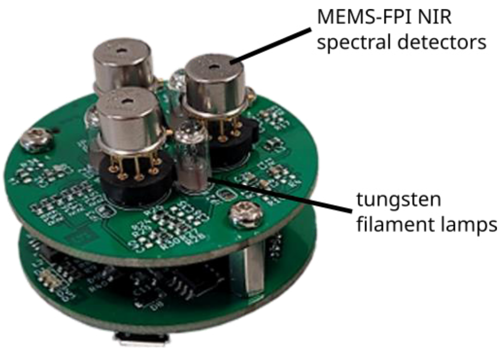

Fig. 2: Miniaturized NIR spectral sensor with MEMS-FPI detectors

Various construction technologies were developed on the basis of the sensor in order to be able to use the prototype in an industrial environment. The arrangement of the detectors and radiation sources plays a particularly important role here. The arrangement and orientation of these two sensor components allows the beam path of the NIR radiation to be significantly influenced and controlled, which increases the quality of the spectral measurement and allows more radiation energy to be used. Figure 3 shows the concept of an NIR spectral sensor for reflectance measurement.

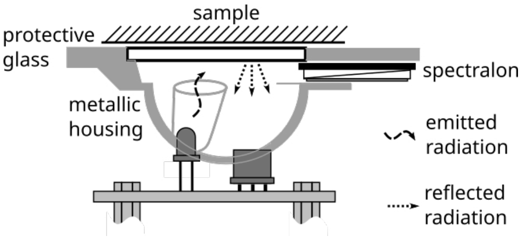

Fig. 3: Sensor concept of an MEMS-based reflection measurement

The signal-to-noise ratio (SNR) of the measurement can be improved by using a metallic housing in the area of the sensor head. The radiation sources can be regarded as spherical radiators whose radiation is emitted equally in all directions. A stainless steel housing, which has a high degree of reflection, allows the radiation to be directed and concentrated on a measuring spot. The use of a metallic housing also offers the advantage of thermal heat dissipation. The NIR detectors are only approved for an operating temperature of up to approx. 75 °C and also exhibit strongly temperature-dependent measurement behavior. By using a metal housing, the heat loss of the radiation sources can therefore be effectively dissipated.

Optical crown glass is used as a protective glass between the sample material and the sensor system. This is characterized by a high transmission coefficient in the NIR range. This glass can also be produced with a (broadband) anti-reflection coating (BBAR), which prevents interfering reflections on the surface between the phases and thus improves transmission. Sapphire glass is also suitable for harsh operating environments, as it is considerably less susceptible to scratches and other damage due to a approximately 3 to 4 times larger Knoop hardness. To integrate the sensor into a process chain for spectral measurement of a fluid, it is preferable to align the protective glass and the sensor head at an angle to the direction of flow. This improves the coupling of the radiation into the fluid. In addition, alignment at an angle to the direction of flow has the advantage that a continuous flow occurs at the protective glass, which counteracts contamination.

An important element in the design of an NIR sensor that works reflectively, as shown in Figure 3, is the integration of a reflection standard. Since the optical properties (emission, transmission, reflection) of the radiation sources as well as the detectors and other optical components located in the beam path depend on various influencing factors, such as temperature and humidity, reference measurements must be carried out. These measurements must be carried out regularly and as required and serve as a kind of calibration of the measuring system. A Spectralon made of sintered polytetrafluoroethylene (PTFE) is generally used as the reflection standard for NIR spectrometers. This has an extremely high and uniform reflectance (> 95 %) in the NIR range. Using a linear actuator, this can be moved in front of the protective glass as required in order to carry out the reference measurement.

The sensor shown above works by means of reflection, i.e. the sample to be measured is illuminated and the (diffuse) reflected radiation is measured by the detector. The implementation of an NIR sensor, which works according to the principle of transmission, is also possible. In this measurement method, the radiation sources are located opposite the detectors. The radiation passes through the sample material and is transmitted to the detector. The prerequisite for this method is that the sample material must be optically permeable to a certain degree. This measurement method is therefore unsuitable for media that are impermeable to NIR radiation. Figure 4 shows the arrangement of the relevant optical sensor components. The optical path length is the distance traveled by the radiation through the sample material. A standard length of 10 mm is suitable here. Shorter lengths are also conceivable with corresponding opaque samples. Another advantage here is the spatial separation of the radiation source from the detector. This means that the detector does not heat up due to the hot radiation source. In this case, the reference measurements are carried out when the channel between the radiation source and detector is empty or filled with a defined medium.

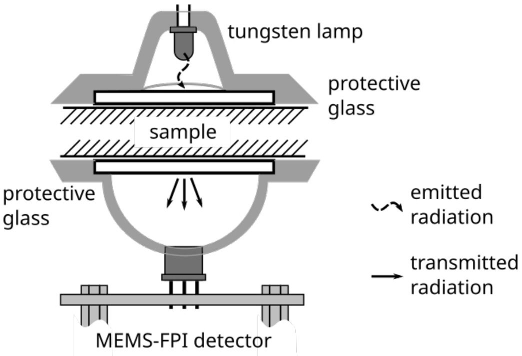

Fig. 4: Sensor concept of an MEMS-based transmission measurement

It is also possible to apply the sensor using an optical fiber probe. This approach has the great advantage of spatial separation between the sample material and the sensor. Particularly in an industrial environment and integration in inline or online process chains, mechanical coupling of interfering vibrations can occur, which has a negative effect on the measurement behavior of the sensor or detector. By using a fiber probe, however, it is possible to decouple the mechanical vibrations. A collimating lens can also be integrated into the fiber probe, which enlarges the measuring spot and thus increases the quality of the measurement. In this way, it can also be used in very hot places, such as those found in plastics processing (injection molding).

Influencing measurement factors

MEMS-FPI NIR spectral detectors consist of two mirrors facing each other. By applying an electrical voltage, the distance between the mirrors can be varied, which controls the transmitted wavelength resulting from the constructive interference. Due to this physical-mechanical operating principle, the detector is sensitive to thermal and mechanical interference factors. Moisture, on the other hand, has no direct influence as the detector is encapsulated in an airtight housing.

The influence of mechanical vibrations and shocks was investigated using a shaker. The NIR sensor was placed in the middle of the shaker for this purpose (Figure 5). In order to be able to investigate only the influence of mechanical vibrations on the detectors, the radiation sources that would contribute to heating were switched off. Instead, an NIR LED was placed directly in front of the detector, which emits a constant, narrow-band spectrum.

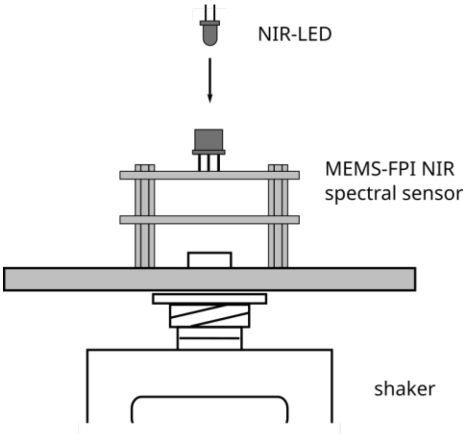

Fig. 5: Experimental setup for the investigation of mechanical influences on MEMS-FPI detectors

The shaker enables mechanical shocks and vibrations that can be varied in terms of strength and frequency. It was shown that even small mechanical vibrations have a considerable influence on the measured values. This behavior was to be expected, as the NIR detector contains miniaturized micromechanical components that are moved out of position when mechanical influences are coupled in, which affects the spectral measurement. The vibrations indicate that the FPI element cannot keep the mirror position of the optical oscillator constant, which makes the measurement unusable. If a critical impulse force is exceeded, the detector is destroyed.

The measurements to investigate the temperature behavior of the NIR detectors were carried out in a climatic chamber. An NIR LED was placed directly in front of the detector, as the emitted radiation characteristics of the radiation sources also depend on the temperature and this influencing parameter should be eliminated. The climatic chamber was then used to set different temperatures and observe the effects on the measured spectra in parallel.

The results of the spectral measurements at different temperatures are shown in Figure 6. It can be seen that the temperature change leads to a distortion of the spectral measurement in the horizontal (wavelength) and vertical direction (intensity). An intensity change of approx. +5 % and a wavelength shift of the peak of approx. 8 % (-24 nm) could be observed at a temperature change of 30 Kelvin. However, the distortion is not linear over the spectral range, as can be seen in Figure 6.

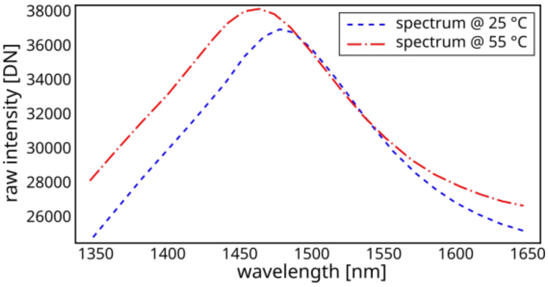

Fig. 6: Influence of temperature on the spectral measurement of MEMS-FPI detectors

The MEMS-FPI NIR detectors have integrated temperature-dependent resistors (Negative Temperature Coefficient - NTC). The thermistors can be used to determine the temperatures directly and separately for each detector. This temperature information can be taken into account when controlling the FPI elements. Feedback allows the temperature drift of the detectors to be compensated and the measurements to be stabilized. Individual component constants were determined for this purpose, which are incorporated into the determination of the control voltage of the FPI element and compensate for the drift due to the temperature change accordingly.

After this compensation was performed, measurements were carried out again with the spectral sensor at different temperatures. This showed that the compensation was successful and the sensor recorded a constant spectrum regardless of the temperature. The change in intensity and wavelength shift at a temperature difference of 30 Kelvin amounted to less than 1 %. As long as the detectors are operated within the specified temperature range, measurement is therefore possible without measurement deviations.

Conclusion

The use of MEMS-FPI NIR spectral detectors in industry and process analysis opens up many new areas of application. Thanks to their compact design and comparatively inexpensive technology, future use in various technical application scenarios is conceivable.

MEMS NIR detectors enable the implementation of different measuring principles that have advantages and disadvantages. For example, reflection measurement can be used to measure solids and non-transparent liquids. Transmission is suitable for transparent liquids, films and gases. By coupling an optical fiber probe, the measuring location can be spatially separated from the sensor. This eliminates thermal and mechanical interference that would be transferred from the measurement location to the sensor.

The main external factors that negatively influence the measurement result of the MEMS-FPI spectral detector are mechanical and thermal interferences. Mechanical disturbances in the form of shocks or vibrations cause a measurement error that cannot be compensated for algorithmically; in this case, the measurement must be discarded. Under these circumstances, mechanical decoupling, e.g. using a fiber probe, is necessary. If the vibrations are too strong, the detector will be mechanically destroyed. Thermal influences cause a drift in the intensity and wavelength of the detector's measurement results. However, this drift can be taken into account and fully compensated for by feedback of the temperature and its consideration when determining the control voltage of the FPI element. This means that the temperature has no negative influence on the measurement result.

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Literature

[1] Yakubu, H. G.; Kovacs, Z.; Toth T.; et al.: The recent advances of near-infrared spectroscopy in dairy production – a review. Critical Reviews in Food Science and Nutrition, 2020, 62:3, 810-831, DOI: 10.1080/10408398.2020.1829540

[2] Mancini, M.; Mircoli, A.; Potena, D.; et al.: Prediction of pellet quality through machine learning techniques and near-infrared spectroscopy. ScienceDirect, Computers & Industrial Engineering, 2020, 147, DOI: 10.1016/j.cie.2020.106566

[3] Chung, H; Ku, M.-S.: Near-Infrared Spectroscopy for On-Line Monitoring of Lube Base Oil Processes. Appl. Spectrosc. 57, 2003, 545-550

[4] B. Bec, K.; Grafska, J.; W. Huck, C.: Principles and Applications of Miniaturized Near-Infrared (NIR) Spectrometers. Chem. Eur. J. 2021, 27, 1514, DOI: 10.1002/chem.202002838

[5] Otto, J.; Krieger, K.-L.; Andreesen, H.: Development of a compact NIR sensor using MEMS-FPI NIR spectral detectors. VDE Verlag, ITG-Fachbericht 303, 2021, Sensoren und Messsysteme - Beiträge der 21. ITG/GMA-Fachtagung: 192-199