



Dual-channel mid-infrared sensor based on tunable Fabry-Pérot filters for fluid monitoring applications

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ABSTRACT

In this article, the design and application of an optical sensor for fluid monitoring based on two tunable Fabry-Pérot filters is presented. The sensor enables fluid transmission measurements in the spectral ranges from 1818 cm^{-1} to 1250 cm^{-1} and from 1250 cm^{-1} to 952 cm^{-1} at wavenumber-dependent resolutions between approximately 20 cm^{-1} and 33 cm^{-1} . A novel method is proposed to ensure a correct wavenumber representation of the obtained spectra, correcting for an oblique light path in the optical system. The sensor shows high linearity and a low noise level for absorbance measurements. As an example for a fluid monitoring application, the transmission spectra of deteriorated automotive engine oil samples were measured and compared to spectra obtained with a Fourier-transform infrared spectrometer. We used partial least squares (PLS) regression to construct calibration models for the prediction of significant oil condition parameters, like oxidation, sulfation, water content and viscosity, from the obtained spectra. The values predicted from the absorption spectra show high correlation with reference values of the oil condition parameters determined in a laboratory according to appropriate standards. These results indicate that the sensor can be a useful supplementary tool for fast and cost-effective engine oil condition monitoring.

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1. Introduction

Increasing requirements in process and condition monitoring lead to an increasing demand for cost-effective, robust and compact sensors. Here, the sensors are usually used in handheld operation or are permanently installed for online operation in harsh industrial environments and must enable a comprehensive analysis of significant process parameters. Systems based on mid-infrared (MIR) spectroscopy have proven particularly useful in this regard as they can provide detailed information on the molecular composition of liquid, gaseous and solid analytes [1–4]. Fourier-transform infrared (FTIR) spectrometers have been established as a standard method for infrared spectroscopy due to their good signal-to-noise ratio and high spectral bandwidth and resolution. Despite the fact that rugged spectrometer models suitable for industrial use are available today, they are rather high priced due to their complex mechanical design containing moving parts.

Featuring no moving parts, static FTIR spectrometers are better suited for the use in harsh environments, but rely on the use of spatially resolving detector arrays [5,6]. Due to the high cost of detector

arrays sensitive in the MIR wavelength region, the use of these systems is limited to applications with high demands regarding measurement speed and spectral resolution.

Other approaches in infrared spectroscopy are based on optical systems using gratings [7–9] or linear variable filters [10–13] for the spectral separation of light. Since these systems operate without moving parts as well, they are also dependent on the use of spatially resolving detector arrays.

Infrared sensors based on external cavity quantum cascade lasers (EC-QCL) have already been presented for the spectroscopic analysis of fluids [14,15] and gases [16,17]. Due to the high light output of the EC-QCL as well as the good collimation, these systems are suitable for the investigation of strongly absorbing samples or in measurement setups with long optical paths. The high cost of EC-QCLs, however, allows the economical use only in a few applications with special requirements for high light intensity and measuring speed.

For cost-effective quantitative analysis, non-dispersive infrared (NDIR) sensors based on optical filters are well established. Numerous implementations of this sensor type have been presented for measuring fluids [18–21] and gases [22–24]. A common disadvantage of this type of sensor is that the used optical filters have to be configured for the absorption bands of characteristic molecules,

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requiring the NDIR sensors to be specifically designed for a particular application.

A promising compromise between cost-effective NDIR sensors and expensive MIR spectrometers could be sensors based on miniaturized tunable Fabry-Pérot filters (FPF). They enable a more flexible adaptation to different measurement tasks than NDIR sensors and are available at low cost through the use of micro-electro-mechanical system (MEMS) fabrication technologies [25–27]. For applications that do not depend on high spectral resolution or measuring speed, but focus on small size and cost-efficiency, integrated FPF detectors represent an interesting alternative. Setups using a single tunable FPF have been presented for various sensing applications [28–31]. Furthermore, efforts were made to expand the spectral range of integrated FPF detectors by separating two interference orders with a dichronic beamsplitter [32].

In this work, we present an optical sensor for fluid monitoring using two miniaturized tunable FPF detectors and a pulsed thin film infrared light source. Using two FPF detectors with different spectral tuning ranges, the sensor covers a broad spectral region with an adequate resolution. We present a method to correct the wavenumber shift in the measured spectra resulting from the oblique light path in the optical system and analyze typical performance characteristics of the sensor. To evaluate the sensor performance in a typical fluid sensing application, we measure the absorption spectra of used automotive engine oil samples. We then apply multivariate data analysis methods to extract significant condition parameters like water content, oxidation and viscosity of the oil samples.

2. Materials and methods

2.1. Tunable fabry-Pérot filter

The optical measurement setup presented in this work utilizes two off-the-shelf miniaturized tunable FPF detectors supplied by Infratec. They consist of a MEMS based Fabry-Pérot interferometer and a pyroelectric element to filter and detect incoming radiation in the mid-infrared wavenumber region from 1818 cm⁻¹ to 1250 cm⁻¹ (LFP-5580C-337) and 1250 cm⁻¹ to 952 cm⁻¹ (LFP-80105C-337). An external drive voltage must be applied to tune the filter to the desired transmission spectrum. The application-specific integrated circuit (ASIC) included in the sensor housing measures the distance d between the interferometer mirrors and thus enables a closed loop control of the drive voltage, eliminating the influence of acceleration forces on the interferometer mirrors. An approximation of the transmission spectrum of a Fabry-Pérot interferometer is given by Eq. (1) [33].

$$T(\tilde{\nu}) = T_{\max} \frac{1}{1 + F \sin^2(2\pi \tilde{\nu} n d \cos \varphi)} \quad (1)$$

Here, $T_{\max}$ is the maximum transmission, $\tilde{\nu}$ is the wavenumber and φ is the angle of the incident light. The coefficient of finesse $F = 4R/(1 - R)^2$ depends on the mirror reflectance R [33]. A medium with the refractive index n is located between the interferometer mirrors. As Eq. (1) exhibits maxima at multiple wavenumbers, an appropriate optical bandpass filter is included in the FPF detector housing to select only one, often the first, interference order of the transmission spectrum. The wavenumber $\tilde{\nu}_0$ of maximum transmission in the first order FPF transmission spectrum is approximated by Eq. (2), φ being the angle of incidence [33].

$$\tilde{\nu}_0 = \frac{1}{2nd \cos \varphi} \quad (2)$$

For normal incidence ($\cos \varphi = 1$), the relation between mirror distance d measured by the ASIC and $\tilde{\nu}_0$ is factory-calibrated for each

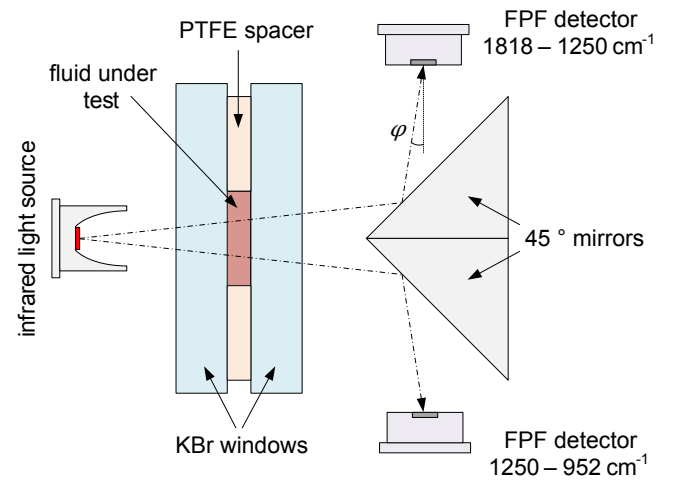


Fig. 1. Optical setup illustrating the functional principle of the presented dual-channel FPF fluid sensor.

individual sensor. However, for incidence angles other than normal, the wavenumber of maximum transmission $\tilde{\nu}_0$ shifts towards higher wavenumbers. When using the FPF detectors in the optical setup proposed in Section 2.2, this dependency must be considered to ensure an accurate wavenumber representation of the measured spectral data.

2.2. Dual FPF sensor setup for fluid measurement

Fig. 1 shows a schematic overview of the presented FPF fluid sensor setup. It consists of a MEMS based thin film infrared light source (Micro-Hybrid JSIR350) with a reflector, a fluid transmission cell with potassium bromide (KBr) windows of 5 mm thickness and a 100 μm Polytetrafluoroethylene (PTFE) spacer, two gold plated mirrors and two tunable FPF detectors covering a combined spectral range from 1818 cm⁻¹ to 952 cm⁻¹. The light source emits radiation in the mid-infrared wavelength region that travels through the KBr windows of the measurement cell and the fluid under test. Depending on the chemical composition of the fluid, the irradiated light is absorbed at characteristic wavenumbers of the infrared spectrum. The transmitted beam of light is then divided by two mirrors at an angle of 45° and reflected on the miniaturized FPF detectors at an angle φ . Within the FPF detectors, the light is filtered by the Fabry-Pérot filter and subsequently detected by a pyroelectric detector element. Because the pyroelectric detector only responds to a change in radiant flux, the light source is modulated. By stepwise tuning of the FPF transmission, a quasi-continuous infrared spectrum can be recorded. After each step, a waiting time of 10 ms is necessary to ensure that the mirrors of the Fabry-Pérot filter are settled.

While the two FPF detectors combined with a second light source could simply be placed side by side at the transmission cell, the setup presented in Fig. 1 offers some advantages. With only one infrared light source, the system cost is reduced and possible issues caused by differing emission spectra and aging characteristics experienced with the use of multiple light sources are prevented. In the setup depicted in Fig. 1, the free aperture of the transmission cell only needs to match the aperture of the single light source, in this case about 7 mm in diameter. Thus, the size of the transmission cell windows can be kept small, which reduces the system cost. Moreover, the force on the windows due to the fluid pressure inside the cell is reduced, improving the pressure resistance in high pressure applications. This relationship is illustrated by Eq. (3): The maximum allowed pressure $P_{\max}$ on a round window is inversely proportional to its free aperture D , where S_F is

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