Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 120 (2015) 392 – 395

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2015

A miniaturized optical sensor with integrated gas cell

N. P. Ayerden*, M. Ghaderi, G. de Graaf, R. F. Wolffenbuttel

Electronic Instrumentation Laboratory, Faculty of EEMCS, Delft University of Technology, Delft, Netherlands

Abstract

The design, fabrication and characterization of a highly integrated optical gas sensor is presented. The gas cell takes up most of the space in a microspectrometer and is the only component that has so far not been miniaturized. Using the tapered resonator cavity of a linear variable optical filter as a gas cell enables ultimate miniaturization, while maintaining robustness without any moving parts. Multiple reflections from highly reflective mirrors allow a 24-25.5 μm long resonator cavity to also act as a gas cell with an equivalent optical absorption path length of 6 mm.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of EUROSENSORS 2015

Keywords: Infrared spectroscopy; gas sensor; Fabry-Perot; linear variable optical filter; Bragg reflector

1. Introduction

Monitoring the composition of distributed natural gas is crucial for safe and clean combustion. The increase in natural gas import and the addition of sustainable energy sources such as biogas in the gas grid results in a rather dynamic composition. This requires small, robust, and low-cost gas sensors that can be installed in every household.

Self-referenced and nondestructive optical absorption microspectrometers are highly demanded for on-site substance analysis. The composition measurement of combustible gases by MEMS-based infrared absorption spectrometers with Fabry-Perot interference filters has been previously addressed [1-3]. However, in all these devices the gas cell remains a separate component and the optical filter is tuned by changing the spacing between the mirrors of an optical resonator either dynamically through actuation or statically by creating an array of filters with different spacing.

* Corresponding author. Tel.: +31 (0)15-27-87548.
E-mail address: n.p.ayerden@tudelft.nl

1877-7058 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of EUROSENSORS 2015
doi:10.1016/j.proeng.2015.08.649

Material identification with high accuracy requires spectral measurements over a wavelength range where the sample to be measured has unique patterns. Linear variable optical filters with a tapered resonating cavity are capable of wideband operation without any moving parts [4]. The characteristics of the Fabry-Perot optical filter with an absorbing medium in-between the mirrors was theoretically investigated and it was concluded that extreme high-finesse reflective coatings were required to achieve a long path cell behavior [5]. With the advances in MEMS technology, it is now possible to fabricate highly reflective mirrors with negligible surface roughness and waviness. Therefore, using the tapered cavity of a linear variable optical filter as a gas cell is a promising concept for high reliability, wideband operation and significant size reduction in MEMS-based absorption spectrometers.

2. Sensor design

The fingerprint region of hydrocarbons is in 3.1-3.7 µm wavelength range as shown in Fig. 1. However, an initially long resonator cavity and highly reflective mirrors are required to be able to elongate the optical light path; thus, to use it as a gas cell. An initially long cavity forces the filter to operate at a higher order that limits the bandwidth, i.e. free spectral range (FSR). Therefore, the wavelength range is narrowed down to 3.2-3.4 µm range, where the important changes in the spectra of hydrocarbons occur.

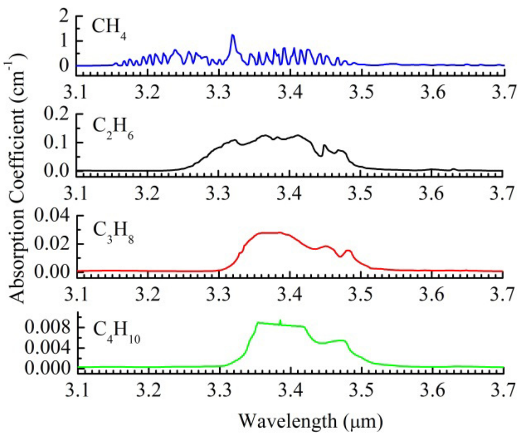

Fig. 1. Absorption coefficient of various gases calculated using typical natural gas concentrations and the NIST database at room temperature for 1 bar total pressure in the 3.1-3.7 µm wavelength range [6].

The optical design of the linear variable filter based on the Fabry-Perot approach has been previously reported [7, 8]. A high-resolution filter with highly reflective mirrors was designed in the 3.2-3.4 µm range. The Bragg reflector, one on each side of the cavity, is composed of 6 alternate layers of sputtered Si (228.41 nm) and SiO_2 (569.97 nm). The first SiO_2 layer of one of the mirrors is tapered (960-2460 nm) to create a tapered cavity (24-25.5 µm) for wideband operation. To analyze the effect of a gas sample in the cavity, methane is introduced as an optical layer in the thin-film design tool.

The Fabry-Perot interferometer consists of two parallel mirrors and a resonator layer in-between. However, in a linear variable filter, one of the mirrors is slightly tilted as in a wedged etalon or a Fizeau interferometer to ensure the wideband operation. For moderate and low reflectivity, the spectral performance of a Fizeau interferometer is highly similar to Fabry-Perot. The spectral response of a Fizeau interferometer with highly reflective mirrors on the other hand, diverges substantially from a Fabry-Perot filter. Therefore, analyzing a linear variable filter as an array of discrete Fabry-Perot filters is acceptable only if the mirrors are not highly reflective.

The transmission of the aforementioned linear variable filter is simulated using the Fizeau model as shown in Fig. 2. Methane is introduced as an absorbing medium with the absorption coefficients extracted from NIST database. The wavelength is selected as 3.32 µm, where the absorption of methane is the strongest. By taking the ratio of the peak transmittance of the filter with methane to the peak transmittance of the filter only, the effect of methane can be calculated. The transmission of methane can then be correlated to the effective optical path length of the cavity using Beer-Lambert Law and the absorption coefficient of methane. The effective optical path length is calculated as 6 mm, which translates into 240 times elongation of the cavity.

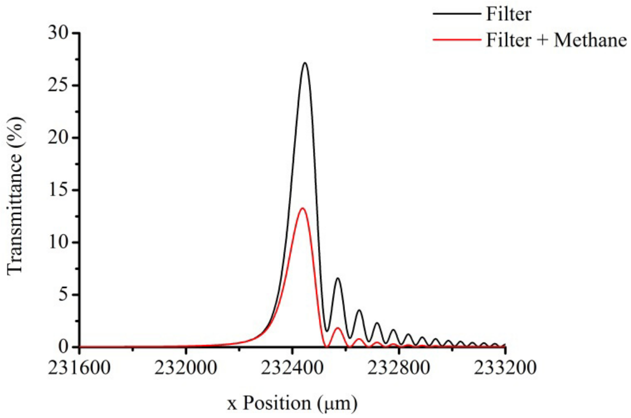

Fig. 2. Transmission response of the filter and filter with methane. x position is the distance from the wedge apex.

3. Fabrication

The fabrication of a tapered SiO_2 layer is based on reflow of a patterned resist and subsequent transfer etching [9]. Both the tapered and the flat reflectors were fabricated by sputtering alternate layers of Si and SiO_2 without breaking the vacuum. These reflectors are subsequently wafer bonded to finalize the fabrication. The profile of the tapered structure is shown in Fig. 3 with a useful level difference of 3 μm between A and A', which covers the required range of 960-2460 nm.

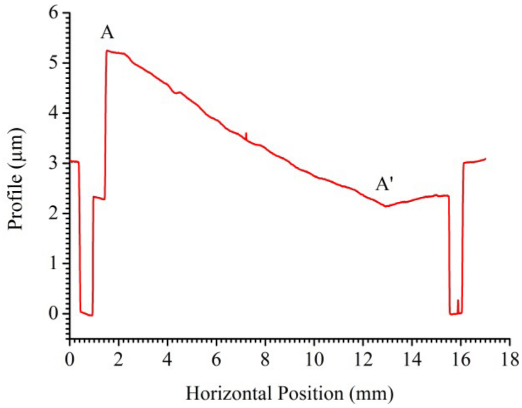

Fig. 3. The measured profile of the tapered mirror.

4. Optical measurements

The optical response of the filter was obtained by scanning through the length of the filter and measuring the transmission with a spectrometer. A 200 μm wide and 3 mm long slit is placed before the filter, and the filter is moved along its length with 2 mm steps. The size of the slit is selected such that the signal can be detected by the spectrometer. However, the large size of the slit compared to the expected width of the transmission curve, the uncollimated nature of the light and the fact that the distance between the filter and the detector cannot be controlled make the FTIR measurement results hard to analyze. Although the curves are widened and exhibit lower transmittance, they move towards longer wavelengths at positions with longer cavity as shown in Fig. 4, which proves the wideband functionality of the filter.

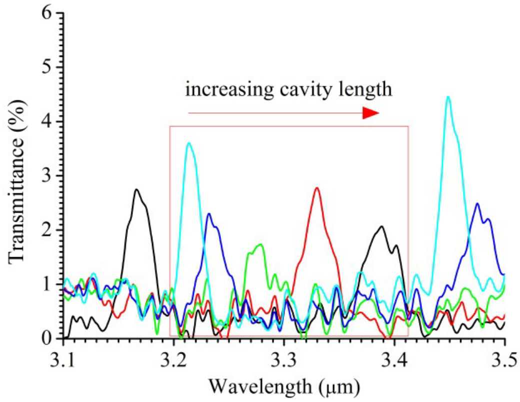

Fig. 4. FTIR measurement of the filter.

The authors are currently working on measurements with a highly collimated laser to characterize the filters in detail with narrower slits.

Acknowledgements

This work has been supported by the Dutch technology foundation STW under grant DEL.11476. The devices have been fabricated at DIMES Technology Centre of TU Delft and Nanofabrication Laboratory of Chalmers University of Technology.

References

[1] R. Mannila, M. Tuohiniemi, J. Mäkynen, I. Näkki, and J. Antila, "Hydrocarbon gas detection with microelectromechanical Fabry-Perot interferometer," in *SPIE Defense, Security, and Sensing*, 2013, pp. 872608-872608-9.
[2] N. Neumann, M. Ebermann, S. Kurth, and K. Hiller, "Tunable infrared detector with integrated micromachined Fabry-Perot filter," *Journal of Micro/Nanolithography, MEMS, and MOEMS,* vol. 7, pp. 021004-021004, 2008.
[3] R. Rubio, J. Santander, J. Fonollosa, L. Fonseca, I. Gràcia, C. Cané, M. Moreno, and S. Marco, "Exploration of the metrological performance of a gas detector based on an array of unspecific infrared filters," *Sensors and Actuators B: Chemical,* vol. 116, pp. 183-191, 7/28/ 2006.
[4] N. P. Ayerden, M. Ghaderi, M. F. Silva, A. Emadi, P. Enoksson, J. H. Correia, G. de Graaf, and R. F. Wolffenbuttel, "Design, fabrication and characterization of LVOF-based IR microspectrometers," 2014, pp. 91300T-91300T-10.
[5] G. Hernandez, "Fabry-Perot with an absorbing etalon cavity," *Applied Optics,* vol. 24, pp. 3062-3067, 1985/09/15 1985.
[6] NIST Mass Spec Data Center and S. E. Stein, "Infrared Spectra," in *NIST Chemistry WebBook, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard*, ed Gaithersburg MD, 20899: National Institute of Standards and Technology.
[7] N. P. Ayerden, M. Ghaderi, G. de Graaf, and R. F. Wolffenbuttel, "A Lossy Fabry-perot Based Optical Filter for Natural Gas Analysis," *Procedia Engineering,* vol. 87, pp. 1410-1413, 2014.
[8] N. P. Ayerden, M. Ghaderi, G. de Graaf, and R. F. Wolffenbuttel, "Optical design and characterization of a gas filled MEMS Fabry-Perot filter," 2015, pp. 95171N-95171N-8.
[9] A. Emadi, H. Wu, S. Grabarnik, G. De Graaf, and R. Wolffenbuttel, "Vertically tapered layers for optical applications fabricated using resist reflow," *Journal of Micromechanics and Microengineering,* vol. 19, p. 074014, 2009.