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A Lossy Fabry-Perot based Optical Filter for Natural Gas Analysis

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Abstract

A set-up for optical gas composition measurement based on absorption spectroscopy is composed of a white light source, a gas cell and a spectrometer. The Fabry-Perot optical filter is suitable for miniaturization of this system, as it is composed of only two reflectors with a transparent layer in-between. Varying the width of this optical resonator to cover the wavelength range in which the components to be analyzed have specific features, gives the absorption spectrum. The gas cell remains a separate unit in the conventional microsystem and a MEMS is the implementation of the microspectrometer. The ultimate miniaturization requires the monolithic integration of all these components. In the lossy Fabry-Perot filter that is presented in this paper, the gas cell and the microspectrometer are functionally integrated, using a gas-filled resonator in which the optical path is determined by multiple reflections in the resonator cavity itself.

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Keywords: gas sensor; optical filter; infrared; spectroscopy

1. Introduction

Natural gas has been a major source of energy, especially in the Netherlands due to the availability of local resources in Groningen. The depletion of natural resources will force a transition from natural gas of well-known composition (G-gas) towards gas mixtures of less stable composition, which may contain high-calorific-value gas (H-gas), liquefied natural gas (LNG), and biogas [2] (Table 1). This calls for composition measurements to ensure safe and clean combustion and consequently requires small, robust and low-cost gas sensors in high-volume production.

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Table 1: Typical composition of G-gas, H-gas, and LNG.

	CH_4 [mol %]	C_2H_6 [mol %]	C_3H_8 [mol %]	C_4H_{10} [mol %]
G-Gas	82.3	3.07	0.47	0.09
H-Gas	89	5.3	1.3	0.3
LNG	90	6.25	1	2.1

The main components of natural gas are hydrocarbons. Although the most relevant gases have significant absorption peaks in the 3.1-3.7 µm wavelength range, their spectra are very similar (Figure 1). Thus, distinguishing these gases requires a high-resolution spectroscopic technique. Optical absorption spectroscopy is a promising compromise between cost and performance, because of features such as self-referencing and non-destructive *in situ* measurement [3].

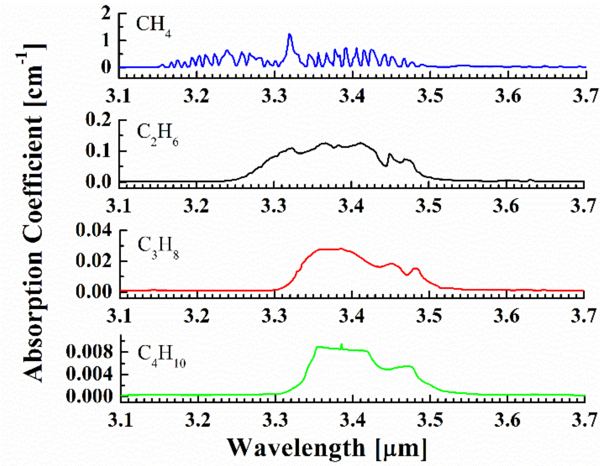

Figure 1: Absorption coefficient of various gases calculated using G-gas concentrations and the NIST database at room temperature for 1 bar total pressure in the 3.1-3.7 µm wavelength range [1].

2. Optical Filter Design

The most essential part of a spectrometer is the optical filter. The Fabry-Perot optical filter which consists of two parallel reflectors and a resonator layer in-between is eligible for miniaturizing a spectrometer. The thickness of the resonator creates a phase shift between the incoming and the outgoing light; thus, determines the wavelength to be transmitted through the filter. The wideband operation of such an optical filter relies on the tuning of the optical path difference between the incident and transmitted light, which requires actuating one of the reflectors. However, actuation is not desired in an application where small and robust sensors are needed.

Our research group has previously reported a Fabry-Perot type linear variable optical filter (LVOF) that operates in the mid-infrared wavelength range [4]. An LVOF is composed of two Bragg reflectors, one flat and one tapered, with also a tapered resonator layer in-between. The continuous linear variation in the resonator thickness results in principle in an array of infinitely many fixed optical filters, where each filter transmits the wavelength that corresponds to the particular resonator thickness at that position. Therefore, with a dedicated detector array, an LVOF is highly suitable for gas sensing, since it covers a wide wavelength range without any moving parts (Figure 2).

A spectrometer is composed of a light source and a sample chamber in addition to the optical filter and the detector array. The sample chamber, in which the light propagates through the sample, occupies the biggest space in a spectrometer. By using the multiple reflections in the resonator layer of an LVOF as the propagation through the sample, one can achieve the ultimate miniaturization of a spectrometer.

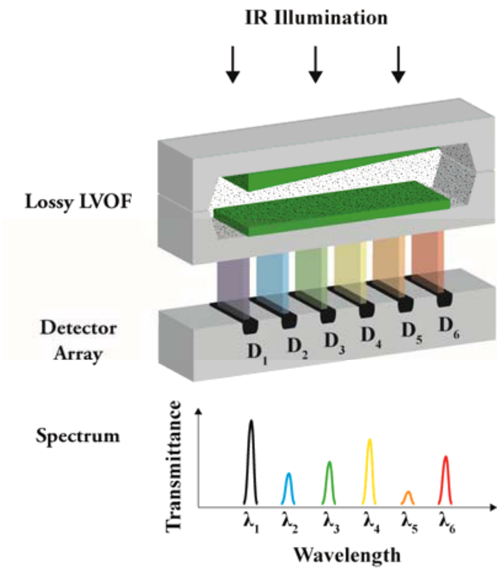

Figure 2: A sketch of the lossy LVOF based microspectrometer.

Fabry-Perot filter with an absorbing etalon cavity was previously investigated in [5]. The concept is similar to a laser; however, it uses a lossy medium instead of a gain medium. The key design issue is to have a sufficiently long absorption path length to ensure a detectable absorption, which requires high mirror reflectance and operation at a high order mode. The mirror reflectance in an optimum design increases with the number of thin-film layers. Operation at a high-order mode reduces the free spectral range (FSR) [6]. Hence, the operating bandwidth of the filter should be tailored as tightly as possible around the band of interest (3.2-3.4 µm). When considering the resonance condition and a reference wavelength of λ_0 = 3300 nm, the maximum operating order results as 15 for an FSR of 200 nm.

A lossy LVOF with 6 alternate layers of silicon and silicon-dioxide is designed using Essential Macleod software (Thin Film Center Inc., Tucson, AZ, USA) [7] (Table 2). For this study, methane is introduced as the resonator with refractive index n=1 and extinction coefficient, k, that is extracted from NIST database [1]. Transmission peaks with sub-nanometer resolution are achieved, which is in agreement with the transmission spectrum of methane of the same concentration that is calculated over 8 mm optical path (Figure 3).

Table 2: Lossy LVOF layers.

Lossy LVOF	#	Layer	Thickness [nm]
mirror 1	1	SiO_2	569.97
	2	Si	228.41
	3	SiO_2	569.97
	4	Si	228.41
	5	SiO_2	569.97
	6	Si	228.41
resonator	**7**	**CH_4**	**24000-25500**
mirror 2	8	Si	228.41
	9	SiO_2	569.97
	10	Si	228.41
	11	SiO_2	569.97
	12	Si	228.41
	13	SiO_2	569.97

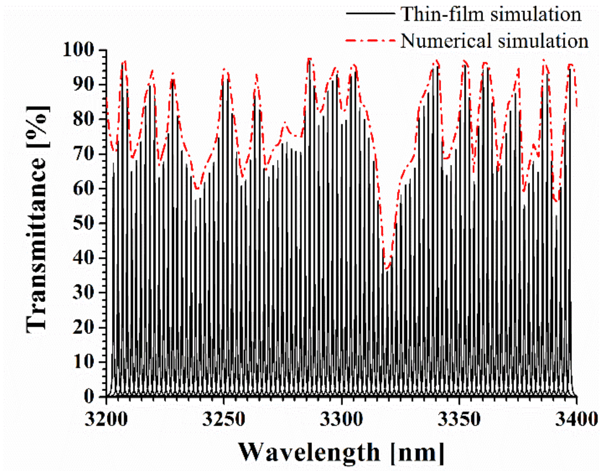

Figure 3: Optical thin-film simulation for 6 layers per mirror lossy LVOF design with methane in the cavity, as compared to the transmittance of methane calculated over an 8 mm optical path. The combined effect of high mirror reflectance (>99%) and thick resonator (24-25.5 µm) results in an effective optical path length of 8 mm.

3. Conclusion

The application of a dedicated MEMS for measuring the composition of combustible gas in the infrared region using optical absorption spectroscopy is investigated. For ultimate system miniaturization, the use of the Fabry-Perot cavity as both optical resonator and sample gas cell is suggested. Preliminary feasibility study shows that an acceptable level of absorption could be achieved at a physical cavity thickness of 24-25.5 µm using multiple reflections, if the resonator is operated at higher modes. Currently, the authors are working on the fabrication of such a device.

Acknowledgements

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