LVOF-BASED IR MICROSPECTROMETER FOR GAS COMPOSITION MEASUREMENT

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***Abstract* — This paper presents the design, fabrication and characterization of Infra-Red (IR) Linear Variable Optical Filter (LVOF) - based microspectrometers. Two LVOF microspectrometer designs have been realized on fused silica glass: one for operating in the 1400 nm to 2500 nm wavelength range and another between 3000 nm and 5000 nm. The IR LVOF has been fabricated in an IC-compatible process using resist reflow. The LVOF provides the possibility to have a small size, robust and high-resolution micro-spectrometer in the IR spectral range on a detector chip. Such IR microspectrometers can be fabricated at low-cost in high volume production and have huge potential in applications such as liquid identification (e.g. water in alcohol, water in oil) and gas sensing.**

***Keywords:* Microspectrometer, gas sensors, IR absorption spectroscopy.**

I - Introduction

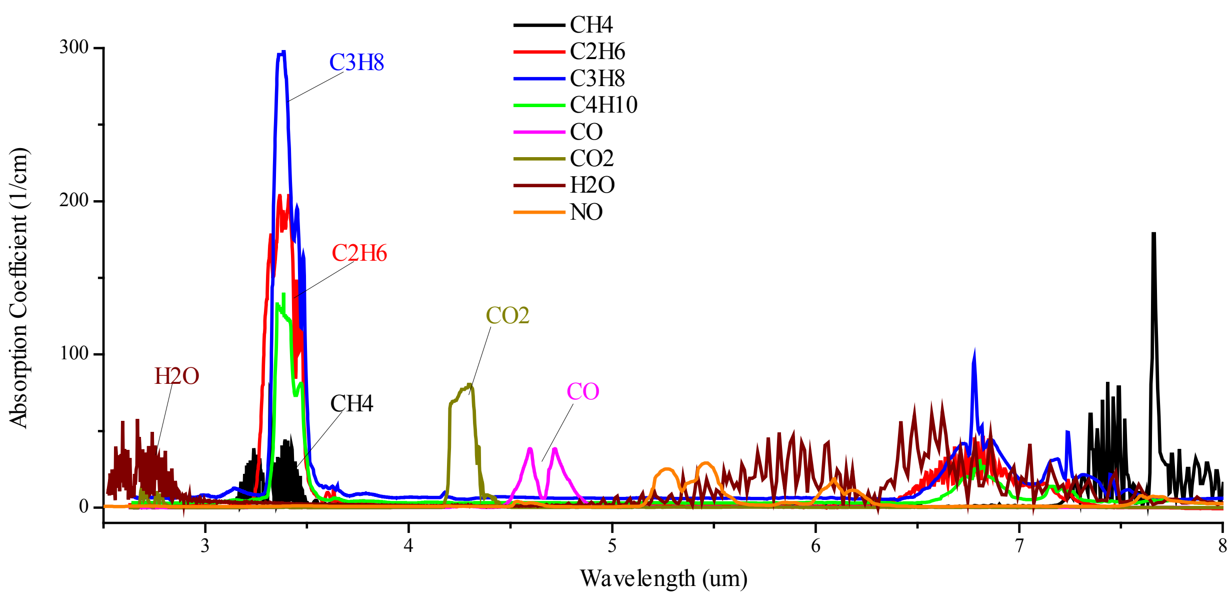
Low-cost single-chip spectrometers have huge potential in systems for biomolecule identification and chemical analysis by optical absorption, fluorescence and emission line characterization. Such microspectrometers offer significant advantages over existing instruments, including size reduction, small sample size, low cost, fast data-acquisition and high reliability. Many interesting gases (e.g. CO, CO_2, N_2O, C_xH_y) have absorption spectra in the 1000 nm – 5000 nm spectral range. Moreover, many liquids (e.g. methanol, ethanol, water, oil) can be identified using their IR spectral absorption signature [1].

A Linear Variable Optical Filter (LVOF) is based on a tapered cavity on top of a linear array of photodetectors and enables the transfer of the optical spectrum into a lateral light intensity profile over the array of photodetectors. The same concept of the system can be designed and realized for wavelengths from UV to IR (300 nm – 5000 nm). The difference is in the choice of the dielectric materials and the layer thickness. In earlier works LVOF microspectrometers for UV and Visible spectral ranges were presented [2]-[3].

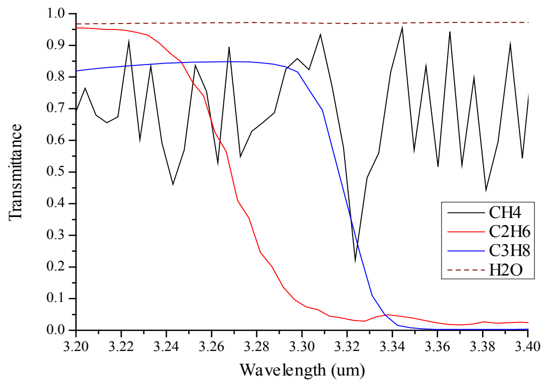
II – Gas Composition Measurement Using IR Optical Absorption Spectroscopy

The wideband IR optical absorption spectrum of several important combustible gases is shown in figure 1. A constraint of absorption spectroscopy on these gases is that reliable measurement is possible only outside the water absorption bands. For this reason, the 3-4 μm band is very interesting for measuring hydrocarbons. Moreover, the 4-5 μm band is interesting for measuring CO and CO_2.

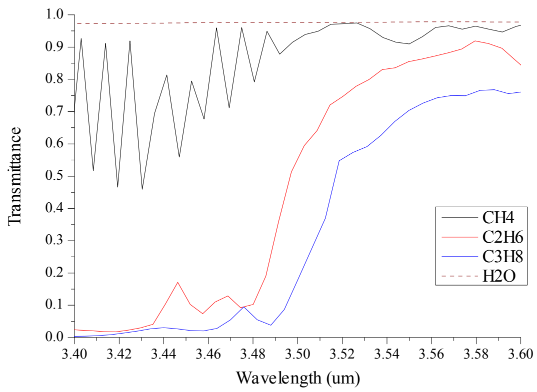
Figure 1: *Spectral absorption lines of gases that are relevant in combustion processes (below).*



This paper is focused on the 3-4 µm band for measuring the hydrocarbon composition. From figure 1 it is clear that the spectra are very similar and data processing will be required to distinguish between methane, ethane and propane. Figure 2 shows two detailed spectral absorption plots that clearly indicated that gas-specific signatures could be derived when measuring with a spectral resolution of about 10 nm.



(a)



(b)

Figure 2: *Details of the transmission spectrum through a 5 cm gas cell.*

II – LVOF-based Microspectrometer Design

Figure 3 shows the schematic of the LVOF microspectrometer configuration, which is a tapered Fabry-Perot type of Linear Variable Optical Filter (LVOF). Collimated light is projected on the surface of the LVOF. The light passing through the LVOF is band-pass filtered determined by the width of the local resonator, and thus by the spatial position along the length of the LVOF [1].

The LVOF is basically a one-dimensional array of many Fabry–Perot (FP)-type of optical resonators. Rather than a huge number of discrete devices, the LVOF has a center layer (the resonator cavity) in the shape of a strip and a thickness that changes over its length. Dielectric mirrors are on either side. Thus the narrow passband wavelength of the LVOF varies linearly along its length. A detector array positioned underneath the LVOF is used for recording the spectrum of the incident light.

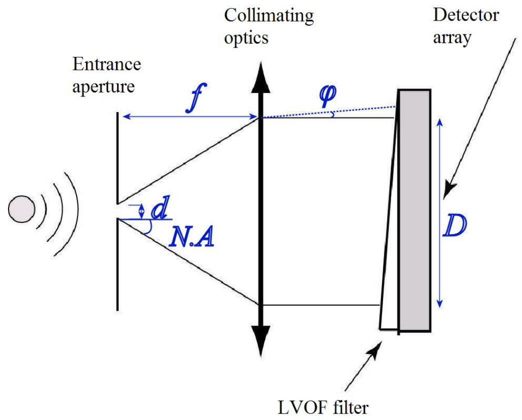


Figure 3: *Basic LVOF microspectrometer configuration.*

LVOF structures have been designed for use in two different parts of the IR spectral band: (a) 1500 nm to 2500 nm and (b) 3000 nm to 5500 nm. Tables 1 and 2 show the designed thickness of the layers used for two multi-layered LVOFs. SiO_2 and sputtered Si have been used as high-*n* and low-*n* materials.

Table 1: *Thickness of the layers for the IR LVOF in the 1500 – 2000 nm wavelength range.*

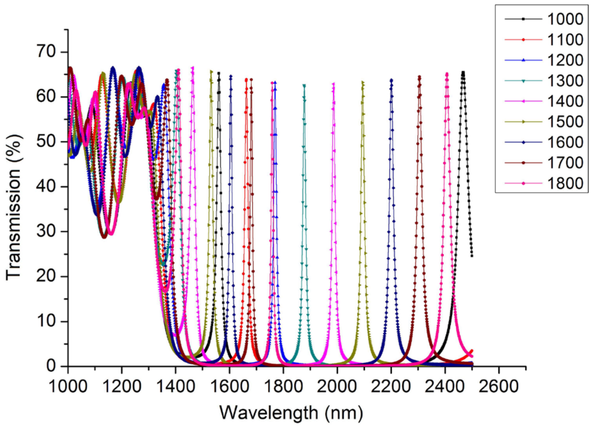
Layer #	Material	Thickness (nm)
1	SiO_2	330
2	Si	125
3	SiO_2	330
4	Si	125
5	SiO_2	**1000–1800**
6	Si	125
7	SiO_2	330
8	Si	125

Table 2: *Thickness of the layers for the IR LVOF in the 3000 – 5500 nm wavelength range.*

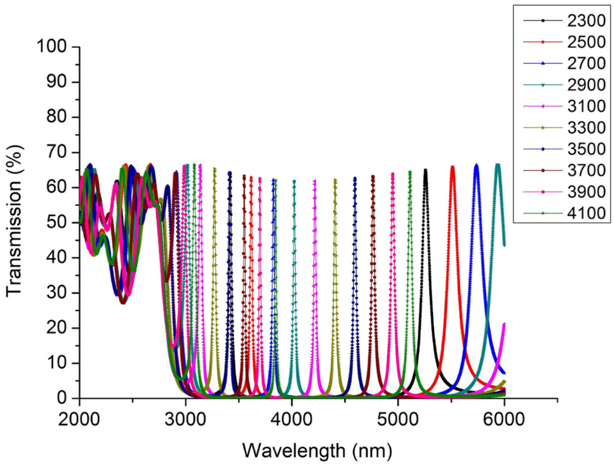
Layer #	Material	Thickness (nm)
1	SiO_2	720
2	Si	270
3	SiO_2	720
4	Si	270
5	SiO_2	**2300–4000**
6	Si	270
7	SiO_2	720
8	Si	270

Figure 4a shows the spectral transmission for LVOF based on Table 1, which is designed to operate in 1500 nm to 2500 nm wavelength range. Figure 4b shows the spectral transmission based on Table 2, which is designed for operation between 3000 nm and 5500 nm.

The thickness of the tapered cavity layer, at the center of the Fabry-Perot filter structure, changes linearly from 1000 nm to 1800 nm in the first design and from 2300 to 4000 nm in the second. The latter covers the intended spectrum and is discussed here in more detail.



(a)



(b)

Figure 4: *(a) Calculated transmission spectrum of IR LVOF in Table 1 for different values of the cavity thickness and (b) calculated transmission spectrum of IR LVOF in Table 2 for different values of the cavity (thickness values are in nm).*

III – IR LVOF Microspectrometer Fabrication

Fabrication has been done in an IC-Compatible process. Initially layers 1-10 have been sputtered on the substrate using a FHR MS 150 sputtering tool, Photoresist has been spin-coated and patterned by a special pattern optimized to produce a linear slope after reflow [4]. The tapered resist pattern has been transferred into SiO_2 cavity layer by a dry-etching process optimized for minimum surface roughness. Figure 5 shows the structure of the completed LVOF from an optical profilometer.

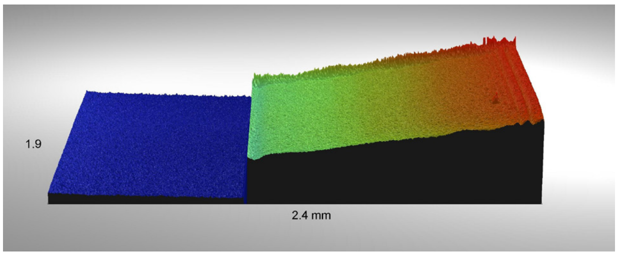


Figure 5: *3D profile of the fabricated IR LVOF as measured by an optical profilometer.*

Figure 6 shows the photograph of a fabricated IR LVOF mounted on a commercially available Pyroelectric IR detector array for characterization.

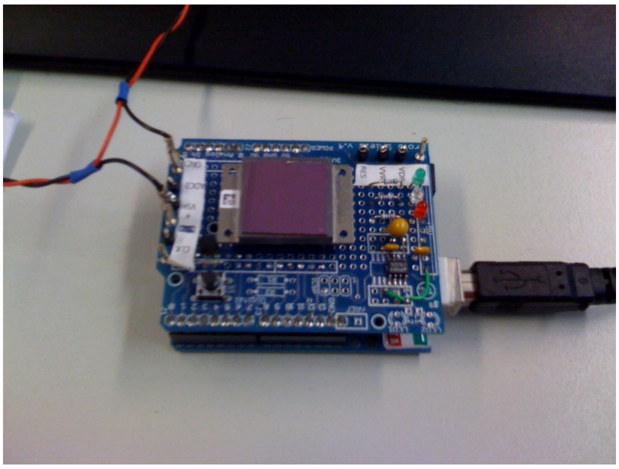


Figure 6: *IR LVOF deposited on Silicon substrate and mounted on a Pyroelectric IR detector array.*

IV – Experimental Results

The position dependent spectral transmission through the IR LVOF was evaluated using a spectrometer set-up, where the LVOF structures was positioned in between the light path between the wideband source and the spectrometer. Sliding the LVOF so that the light spot was projected at several positions along the slope. Taking a scan at each of these positions resulted in as many spectral transmission plots in time. Figure 7 shows a typical set of transmission curves. Note that the filter operates at a higher order mode, which results in the parasitic transmission in the 1-2 μm band. This preliminary characterization confirms a spectral resolution better than 20 nm, which can be further improved after signal processing [5].

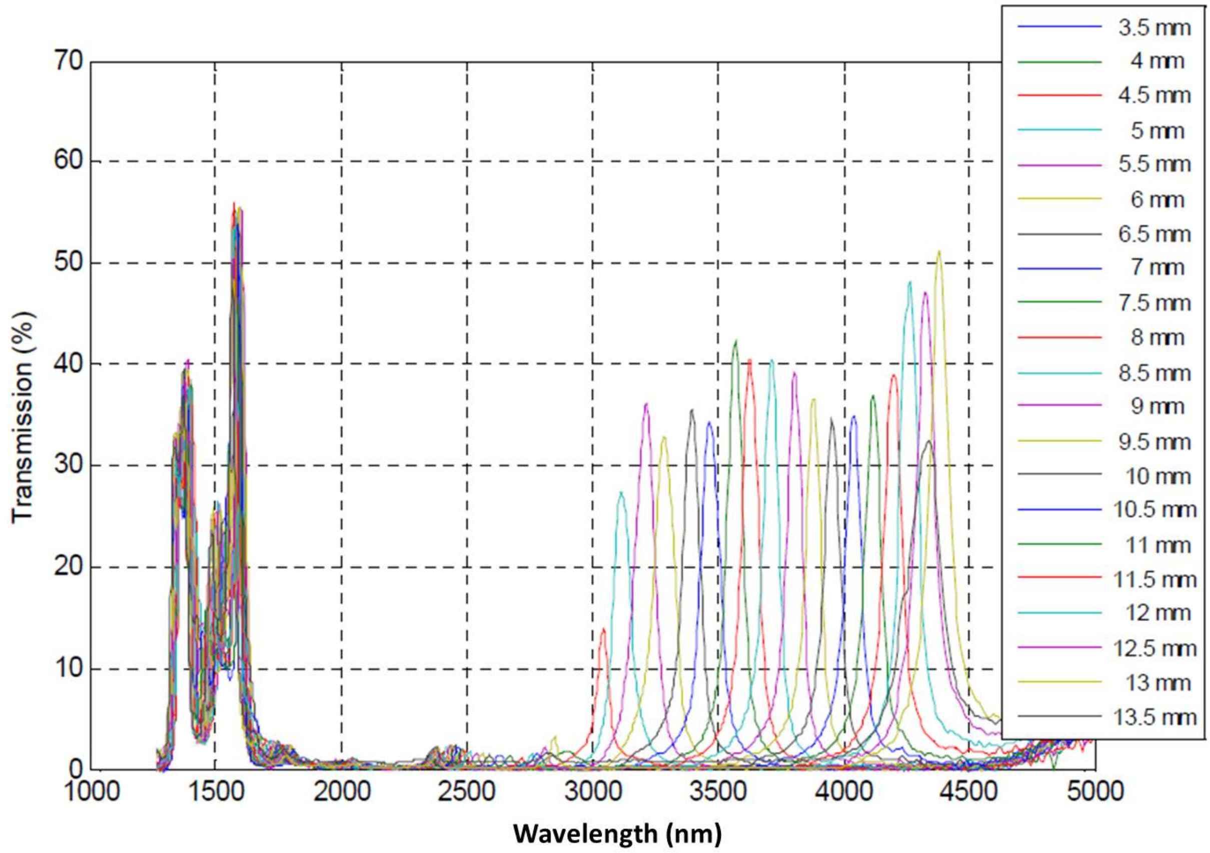


Figure 7: *Set of transmission curves of the IR LVOF with the slided position (i.e. position of the light spot on the slope) is shown in the insert (above).*

On-going research is directed towards the integration of the LVOF with arrays of thermal detectors on a micromachined carrier, as is shown schematically in Figure 8.

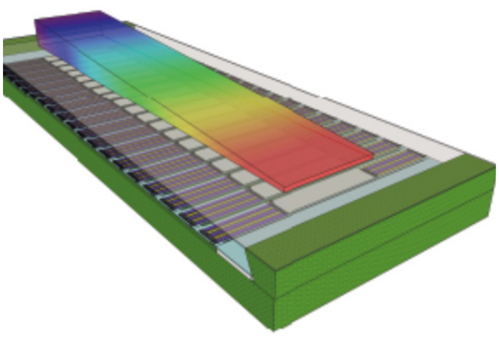


Figure 8: *Artistic impression of the final device.*

Acknowledgments

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References

[1] R. F. Wolffenbuttel MEMS-based optical mini- and microspectrometers for visible and infrared spectral range, *J. Micromech. Microeng.*, vol. 15, pp. 145 2005.

[2] A.Emadi, H. Wu, S. Grabarnik, G. de Graaf, R. F. Wolffenbuttel, CMOS-compatible LVOF-based visible microspectrometer, *Proc. SPIE*, Volume 7680, (2010), pp. 76800W/1-6

[3] A.Emadi, H. Wu, S. Grabarnik, G. de Graaf, K. Hedsten, P. Enoksson, J.H.G. Correia, R.F. Wolffenbuttel, An UV Linear Variable Optical Filter-Based Micro-Spectrometer, *Procedia Engineering*, Volume **5**, Eurosensor XXIV, (2010), pp. 416-419

[4] Emadi, H. Wu, S. Grabarnik, G. de Graaf and R.F. Wolffenbuttel, Vertically tapered layers for optical applications fabricated using resist reflow, *J. Micromech. Microeng.*, Volume 19, (2009), pp. 074014/1-9.

[5] D. Massicotte, R. Morawski, A. Barwicz, Kalman-filter-based algorithms of spectrometric data correction-Part I: An iterative algorithm of deconvolution, IEEE Transactions on Instrumentation and Measurement, Vol. 46, No. 3, June 1997.