

# Enhanced resolution Fabry-Pérot microspectrometers

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## Abstract:

MEMS Fabry-Perot filters ( $\mu$ FPF) are key elements in infrared microspectrometers. First order  $\mu$ FPF, as presented in previous papers [1], exhibit the widest tuning range but their spectral resolution is limited. Some applications, for example the analysis of hydrocarbon gases, require a higher resolution, because the absorption bands of the individual components are similar and widely overlapping. In this work  $\mu$ FPF are presented, which are operated in the third or fourth interference order and can therefore provide a resolution of (20...30) nm in the wavelength range (3.1...3.7)  $\mu$ m. Improved dynamic response of the filter and the combination with a room temperature operated PbSe photodetector allows for the fast acquisition of highly resolved spectra.

**Key words:** Fabry-Pérot filter, tunable infrared filter, microspectrometer, hydrocarbon gases, PbSe photodetector.

## Background

The analysis of hydrocarbon gas mixtures – for example natural gas, biogas or other fuel gases – often requires a very high accuracy and the discrimination of the individual gas components. This is especially important for the determination of the energy content for billing purposes, to control combustion processes and for leakage detection as well. Nowadays, for such sensing tasks the gas chromatograph (GC) is the “Gold-Standard” [2]. But its high costs and the need for a carrier gas are unfavorable. Furthermore, GCs are quite slow devices; a single measurement takes up to some minutes.

A potentially faster and much cheaper measurement method is infrared spectroscopy. Typical IR gas analyzers use one or more detector channels, which are equipped with narrowband optical filters (NDIR principle). Such systems come to their limits if complex mixtures with overlapping absorption bands have to be measured.

In contrast, tunable filters provide a solution by enabling the acquisition of continuous spectra. A spectrometer device with a set of tilting narrow band filters mounted on a rotating stage for the measurement of hydrocarbon gases is described in [3]. It represents some progress beyond the GC technology but the complex mechanics and optics as well as the need for a TE cooled MCT detector are cost drivers.

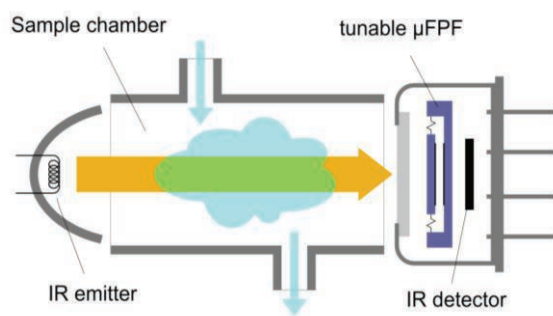


Fig 1. Adaption of the NDIR principle to the use of a MEMS tunable filter

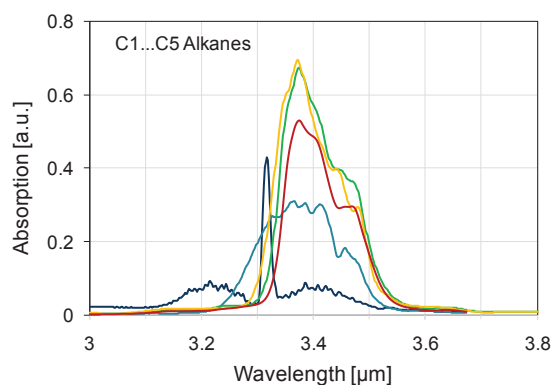


Fig 2. Absorption spectra of the C1...C5 alkanes and CO<sub>2</sub> (qualitative representation). data taken from NIST [6].

The integration of a tunable MEMS FABRY-PÉROT-filter ( $\mu$ FPF) into the detector package results in a much higher degree of miniaturization and lower costs. The NDIR principle can be easily adapted to this kind of microspectrometer devices (Fig 1). Some papers report on the design and application of such systems to the measurement of hydrocarbon gas mixtures [4], [5].

While state-of-the-art first order  $\mu$ FPF have a FWHM bandwidth of about (60...80) nm [1], the applications mentioned above require a much higher resolution, because the spectra of the hydrocarbons, and in particular the alkanes, are very similar (Fig 2). The wavelength range of (3...4)  $\mu$ m is preferred, because of the absorption strength of the C-H stretching modes and the absence of interfering absorptions, first of all water vapor.

### Fabry-Pérot filters with enhanced resolution

An FPF is comprised of two parallel reflector plates. In simple terms, it acts as a half wave resonator, producing a series of transmittance peaks of successive interference orders  $m$  [7]. By changing the plate separation  $d$  the peak positions (center wavelengths  $CWL_m$ ) can be tuned. Tuning is limited in practice by the free spectral range  $FSR$ , which is largest for  $m = 1$  and decreases in higher orders:

$$FSR_\lambda = \frac{2d}{m(m+1)} \quad (1)$$

The spectral resolution of the FPF is given by the peak bandwidth, defined as full width at half maximum ( $FWHM$ ). It can also be expressed in terms of finesse  $\tilde{F}$  or resolving power  $\mathcal{R}$

$$\mathcal{R} = \frac{\lambda}{\Delta\lambda} = \frac{CWL_m}{FWHM_m} \approx m\tilde{F}_E \quad (2)$$

where  $\tilde{F}_E$  is the effective finesse, which is limited for various reasons: Firstly it is defined by the reflectivity but most important by the presence of so called defects (imperfections of the parallel reflector alignment and flatness). Practically achievable figures for first order  $\mu$ FPF with a sufficiently large aperture of about 2 mm are  $\tilde{F}_E = 45...60$ .

Because defects are always limiting the effective finesse, the spectral resolution cannot be further enhanced by increasing the reflectance. Instead, higher interference orders have to be applied and therefore a suitable compromise between tuning range and spectral resolution needs to be found [8]. In addition, the aperture finesse  $\tilde{F}_A$

$$\tilde{F}_A = \frac{8}{m\alpha^2} \quad (3)$$

with  $\alpha$  as the full cone angle of the transmitted beam also contributes to the overall effective finesse  $\tilde{F}_E$  and this is especially important when using higher orders.

### Experimental results

The  $\mu$ FPF used in this work are based on a bulk micromachining approach with two structured wafers bonded together and thick silicon reflector carriers on which the optical layers are deposited. In previous work [8] BRAGG reflectors made from poly-silicon and  $\text{SiO}_2$  have been used. It was now decided to switch to an alternative three material system consisting of Ge, ZnS and  $\text{YbF}_3$ . It has the advantage of a higher refractive index contrast and much more flexibility for the thin film design. As a result, reflectors with a wider stop-band, precisely adjusted reflectance and a high degree of stress compensation can be fabricated (Fig 3).

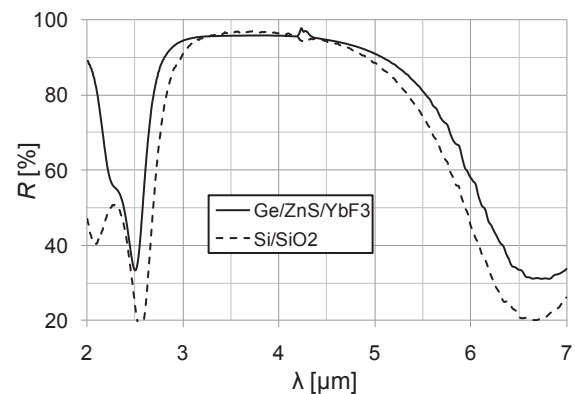


Fig 3. Spectral reflectance of the formerly used reflectors with Si and  $\text{SiO}_2$  (dashed) and the new reflectors (solid) with the materials system Ge, ZnS and  $\text{YbF}_3$  (measured with FTIR, resolution  $8 \text{ cm}^{-1}$ ).

Filters with a tuning range of at least (3.1...3.7)  $\mu$ m and a spectral resolution in the range (20...30) nm need to be operated in the 3<sup>rd</sup> or 4<sup>th</sup> order, as can be derived from equations (1, 2). New prototypes of  $\mu$ FPF in both configurations have been fabricated and tested. Results of the spectral performance are shown in Table 1 and Fig 5.

Table 1. Performance results of the fabricated  $\mu$ FPF, comparison of different order configurations

Order $m$	3	4
Tuning range / $\mu$ m	3.1 ... 3.9	3.1 ... 3.7
$FWHM$ / nm	25 ... 30	20...25
$\mathcal{R}$	$\sim 125$	$\sim 150$

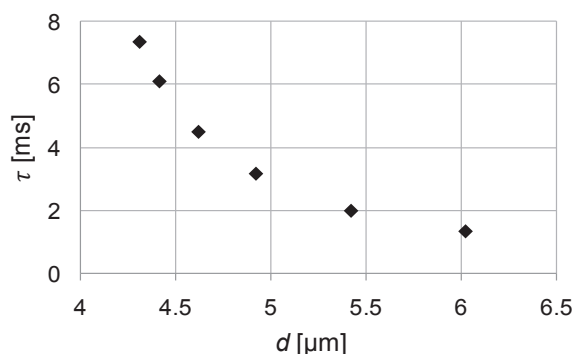


Fig 4. Measured time constants ( $T_{63}$ ) of a  $\mu\text{FPF}$  in 3<sup>rd</sup> order configuration as a function of the reflector distance  $d$  (the range of  $d$  corresponds to a tuning range of about 3.7...3.1  $\mu\text{m}$ , see Fig 5)

The electromechanical design of the filters was completely revised. Now not only one but both reflectors are suspended by springs, resulting in a greatly reduced acceleration sensitivity and improved dynamic response [9]. Time constants of the filters were measured with the Step-Scan FTIR method (Fig 4). They allow for scanning speeds up to 5 Hz in a quasi-static manner or even higher, if dynamic effects like nonlinear damping and electrostatic softening are compensated by a suitable driving method.

### Detector technology

Thermal detectors, for example pyroelectric, are very stable, can be operated at room tempera-

ture and have a broadband spectral response. On the other hand, they are slowly due the thermal time constant and can only detect modulated radiation. The acquisition of a spectrum with such a device has to be performed stepwise and takes a few seconds.

For the mid wave infrared range of (3...5)  $\mu\text{m}$  PbSe photoresistors represent an alternative solution, if higher scanning speeds are needed. They can be operated from DC up to the kilohertz range and therefore open up opportunities for new acquisition methods with fast continuous scanning and without source modulation (so called sweep mode).

When comparing thermal and photodetectors not only the different frequency response but also the spectral response has to be taken into account. Thermal detectors ideally have a flat spectral response, limited only by the properties of the absorber. The spectral response of PbSe photoresistors typically peaks around 4  $\mu\text{m}$ . A comparison of both types of detectors is shown in Fig 6. They show typical performance figures for detectors with a sensitive area of 4 mm<sup>2</sup> at room temperature. As can be seen, the photoresistor is well suited for the measurement of hydrocarbons in the range (3...4)  $\mu\text{m}$ . However, to make use of its full potential the scan rate of the filter have to be further increased.

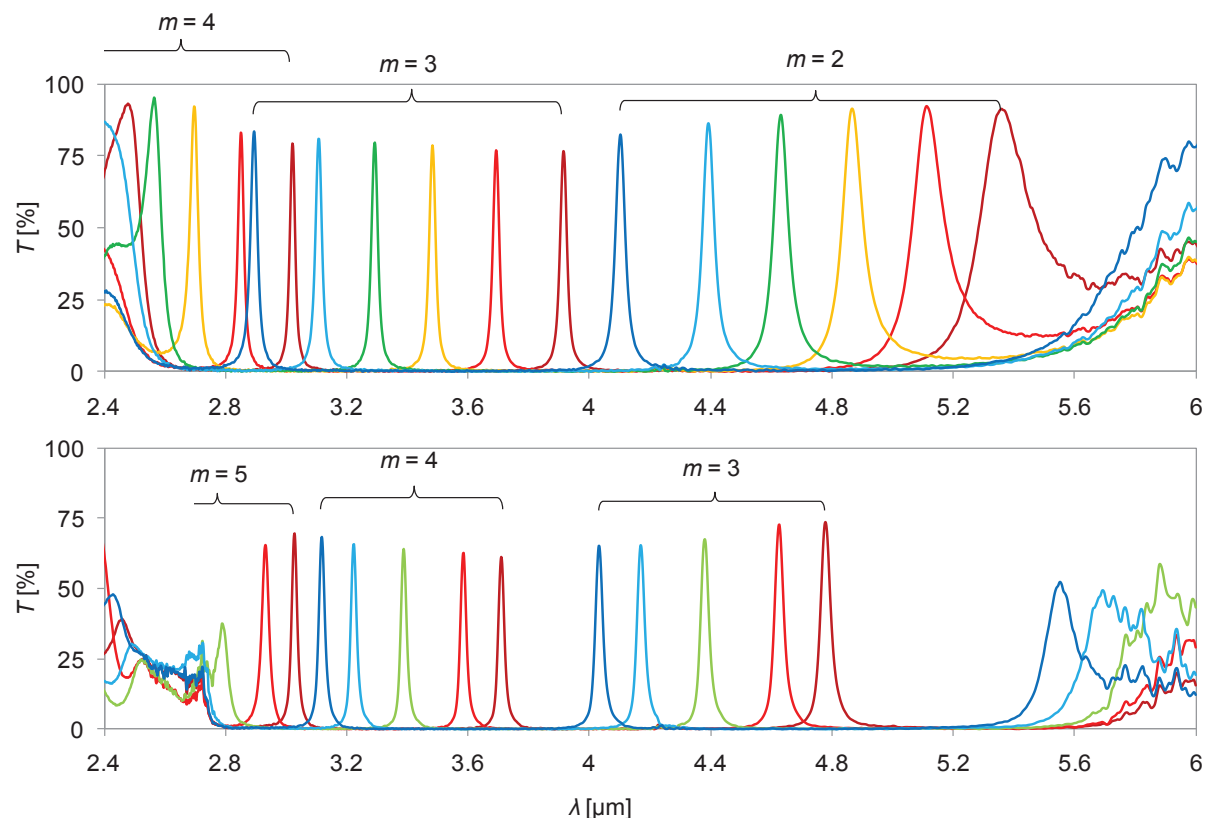


Fig 5. Transmittance spectra of high resolution  $\mu\text{FPF}$  with different configurations of the interference order  $m$ , measured with FTIR, resolution 4  $\text{cm}^{-1}$ , full cone angle  $\alpha = 6^\circ$ .

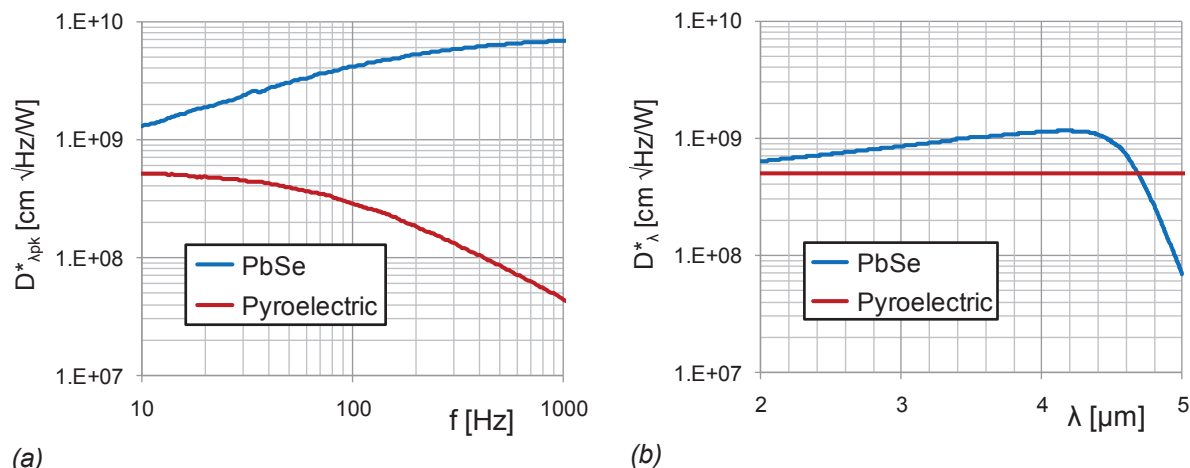


Fig 6. Specific detectivity  $D^*$  of pyroelectric detectors and PbSe photoresistors at room temperature, (a) as a function of frequency ( $\lambda_{pk} = 4 \mu\text{m}$ ) and (b) as a function of wavelength ( $f = 10 \text{ Hz}$ ).

### Test measurements

A prototype of an integrated microspectrometer module with PbSe photoresistor is shown in Fig 7. It was used for several test measurements. Unfortunately, it was not possible to perform measurements with real gases of specific compositions. It was therefore decided to test with a polystyrene (PS) foil, which is commonly used as wavelength standard for mid infrared spectrometers. It exhibits spectral features in the desired range which allows for a good comparison of the spectral resolution of different spectrometers. Fig 8 shows transmittance spectra measured with a high resolving FTIR spectrometer compared to measurements with a  $\mu\text{FPF}$  spectrometer in the 1<sup>st</sup> interference order and with one of the newly developed devices in the 3<sup>rd</sup> order.

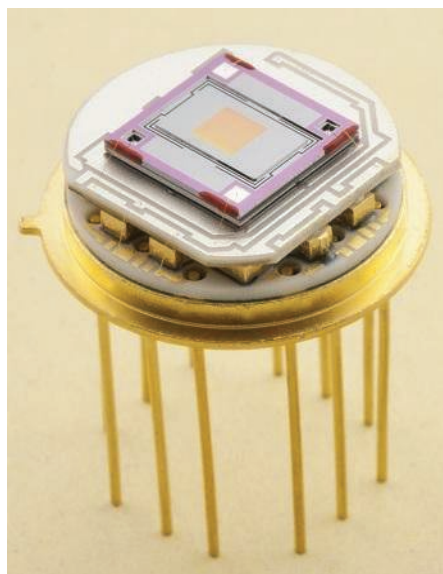


Fig 7. Photograph of the integrated microspectrometer module in a TO-8 housing (without cap)

The results were obtained with the conventional stepwise scanning method with an electrically pulsed IR emitter (10 Hz modulation frequency).

Fast continuous scanning modes are currently under investigation. Detailed results will be reported in the future.

### Summary

A fast and highly resolving  $\mu\text{FPF}$  based spectrometer has been described including design considerations and measurement results of the fabricated prototypes.

Test measurements clearly show the resolution enhancement of the higher order  $\mu\text{FPF}$ , which could be useful for many applications especially for hydrocarbon gas detection.

Future work should be focused on the development and test of fast acquisition modes in combination with room temperature photo-detectors.

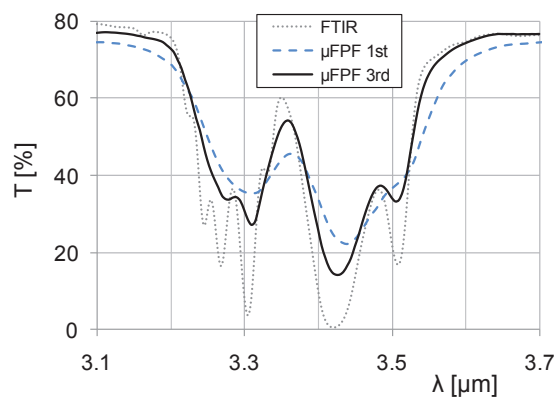


Fig 8. Transmittance spectra of a polystyrene foil measured for comparison with a FTIR spectrometer (resolution  $8 \text{ cm}^{-1}$ ) and  $\mu\text{FPF}$  devices in 1<sup>st</sup> and 3<sup>rd</sup> order configuration.

The authors acknowledge the support by the Federal Ministry of Education and Research of Germany (contract number 13N12037).

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