Out-of-plane translatory MEMS actuator with extraordinary large stroke for optical path length modulation in miniaturized FTIR spectrometers

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Abstract
A translatory MOEMS actuator with extraordinary large stroke – especially developed for fast optical path length modulation in miniaturized FTIR-spectrometers - is presen¬ted. A precise translational out-of-plane oscillation at 500 Hz with large stroke of up to 1.2 mm is realized by means of a new suspension design of the comparative large mirror plate with 19.6 mm² aperture using four pantographs. The MOEMS device is driven electro - statically resonant and is manufactured in a CMOS compatible SOI process. Up to ± 600 µm amplitude (typically 1mm stroke) has been measured in vacuum of 30 Pa and 50 V driving voltage for an optimized pantograph design enabling reduced gas damping and higher driving efficiency.

Keywords: Optical SOI-MEMS, translatory micro mirror, optical path length modulation, Fourier-transform infrared spectrometers, optical vacuum packaging

1 Introduction

Fourier Transform Infrared (FT-IR) spectroscopy is a widely used method to analyze different materials - organic and inorganic. Current FT-IR spectrometers are large, usually static, and are operated by qualified personnel. By using translational MOEMS devices for optical path length modulation instead of conventional highly shock sensitive mirror drives a new class of miniaturized, robust, high speed and cost efficient FTIR-systems can be addressed. An early approach of a miniaturized MEMS based FTIR spectrometer has been developed in the past by IPMS and the CTR [1]. It was a combination of classical infrared optics with a translatory 5 kHz MEMS mirror using a folded bending spring mechanism. Due to the limited amplitude of ± 100 µm a spectral resolution of 30 cm^{-1} was realized allowing dynamic FTIR measurements in the ms-range [2]. To enhance the stroke IPMS introduced a first translational MEMS device with two pantograph mirror suspensions – originally designed for larger stroke of 500 µm. But due to superimposed parasitic torsional modes only ± 140 µm amplitude could be measured [2].

In this paper, we now present an optimized MEMS device which overcomes the previous limitations enabling an extraordinary large stroke of 1 mm. The novel translatory MOEMS actuator was specially designed to enable a miniaturized MEMS based FTIR spectrometer with improved system performance of 5 cm^{-1} spectral resolution (λ = 2.5…16 µm), SNR > 1000 and fast operation of ≥ 500 scans / sec. Hence, a large mirror aperture of 5 mm, enhanced amplitude of ± 500 µm and a small dynamic deformation of < $\lambda/4$ is required. Due to the significant viscous gas damping in normal ambient the translatory MEMS devices have to operate in vacuum – requiring a long term stable optical vacuum package with broadband IR window. The paper discusses the design, fabrication and experimental characteristics of the novel translatory MEMS actuator including first results of the optical vacuum packaging.

To realize a large stroke of the mirror plate a pantograph like suspension was chosen. The new translatory MEMS actuator consists of four symmetric pantograph suspensions in contrast to two pantographs used for a previous MEMS design, where only ± 140 µm amplitude could be achieved due to parasitic tilt modes. One single pantograph consists of six torsional springs – two springs arranged on the same axis – and connected by stiff levers. The torsional springs are used us deflectable elements instead of bending springs which reduces significantly parasitic mirror deformation due to mechanical stress. Due to the optimized mechanical design using 4 pantograph suspensions the new translatory MEMS actuator can provide a precise out-of-plane translation with ± 500 µm amplitude in vacuum of 30 Pa at 50 V. This enables a completely new family of low cost handheld FTIR analyzers with a spectral resolution of up to 5cm^{-1}, 1000 scans/s and SNR > 1000 e.g. applied by individuals for ad-hock inspection of food or environmental parameters. The work was performed in the context of the FP7 project MEMFIS.

2 Translatory Mems Mirror

The novel translatory MOEMS actuator was specially designed to enable a miniaturized MEMS based FTIR spectrometer with improved system performance of 5 cm^{-1} spectral resolution (λ =2.5…16µm), SNR > 1000 and fast operation of ≥ 500 scans / sec. Hence, a large mirror aperture of 5 mm, enhanced amplitude of ± 500 µm and a small dynamic deformation of < λ/4 is required.

2.1 Large stroke MEMS design

The MEMS design have been developed within an iterative process using FEA simulations of single and coupled physical domains and transient simulations of the resulting dynamic behaviors (e.g. frequency response curves) using reduced order models. For the translatory MEMS design the following general specifications and boundary conditions have been considered.

Specification and Boundary Conditions of MEMS design:

Resonance frequency :	f = 500 Hz
Mirror diameter:	D = 500 mm
Mechanical amplitude:	z = ± 500 µm
Dynamic mirror deformation:	$\delta_{p-p} < \lambda / 10$ (λ = 2500 m → δ_{p-p} < 250 nm)
Max. mechanical stress:	s1 ≤ 1.4 GPa
Max. MEMS dimensions:	l x w = 11000 µm x 11000 µm
Max. acceleration	a_{max} = 2000 g
Reflectance of mirror	R @ λ = 2.5 µm…16 µm ≥ 95 %

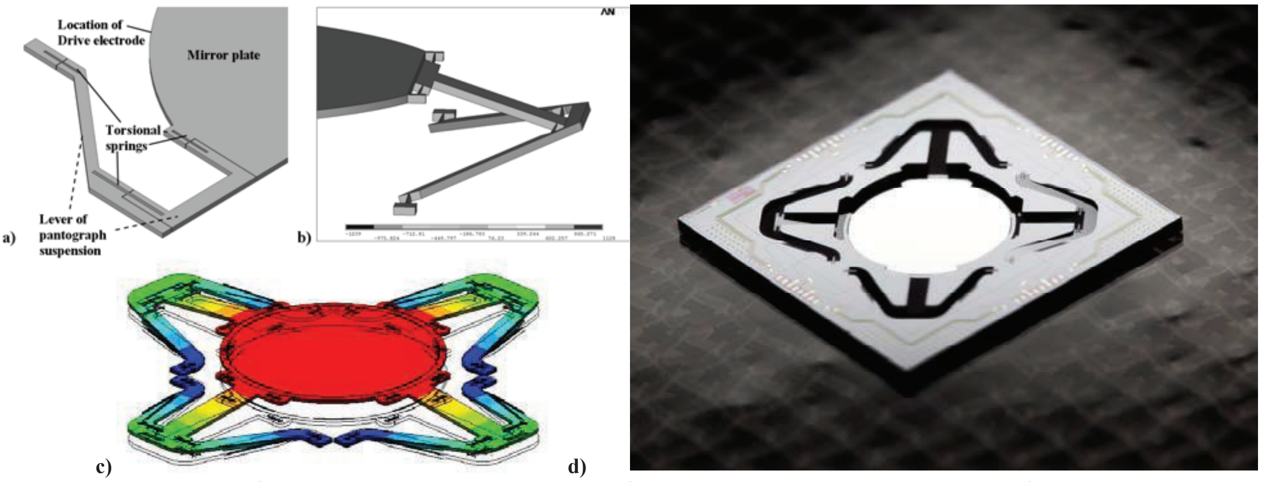

Figure 1. Translatory MEMS design with pantograph suspension of oscillating mirror plate; (a) basic design of the pantograph suspension (detail of a 1/4 plate), (b) previous translatory MEMS device with two pantograph suspensions at 320 µm deflection [2], c) FEA model of new MEMS with four pantograph suspension, d) photograph of new MEMS device @ 400µm pre-deflected.

To realize a large stroke of the mirror plate a pantograph like suspension was chosen. Here, torsional springs are used us deflectable elements instead of bending springs which reduces significantly parasitic mirror deformation due to mechanical stress. For the translatory MEMS devices - presented in this paper - the mirror plate is supported symmetrically by four pantograph suspensions (see figure 1) in contrast to two pantographs used for a first pantograph MEMS design [2], where only ± 140 µm amplitude could be achieved due to parasitic tilt modes [2]. One single pantograph consists of six torsional springs – two springs arranged on the same axis – and connected by stiff leavers. By using four symmetric pantograph suspensions an excellent mode separation for precise translation could be realized for the new translatory MEMS [4]. Beside the modal analysis the following main results were simulated:

For a 5mm mirror MEMS device a dynamic mirror deformation of 433 nm (p-p-value) was simulated. To reduce the dynamic mirror deformation bellow the limit of λ/10 = 250nm (p-p) an alternative MEMS design with slightly reduced mirror diameter of 4.2mm was developed, which results in a smaller dynamic deformation of 220 nm at ± 500 µm amplitude. The required driving voltage was simulated for a vacuum pressure of 30 Pa to maximal $U_D \leq 110$ V bellow the electrostatic stability (pull-in) voltage of minimum $U_{pull-in} \geq 118$ V. The maximal mechanical stresses of typical 1.0 GPa (in the worst case 1.24 GPa) where simulated at maximal mech. deflection of ± 500 µm using nonlinear FEA simulations, which is bellow the limit of ≤ 1.4 GPa. Due to the large moment of inertia about 2 GPa stress occurs at 2000 g acceleration, but for the majority of practical applications it is not crucial.

2.2 Fabrication

The translatory MOEMS device are manufactured in a CMOS compatible SOI process [3] using a highly p-doped device layer of 75 µm. The translatory MEMS actuators are driven electro-statically resonant using in-plane vertical comb drives [3] located on each of the 4 pantographs for optimized driving efficiency (see figure 2). To enable areas of different electrical potential within the same structural SOI plane vertical insulations are required. In contrast to the standard scanner technology of IPMS – where filled insulation trenches are used typically – now for the new translatory MEMS devices reported in this paper only open vertical trenches have been used for electrical isolation of out-of-plane comb drives to simplify the MEMS process. Photographs of finally fabricated translatory MEMS devices are shown in figure 1d and figure 2. For electrical characterization and later vacuum packaging the MEMS chips are chip bonded on a ceramic wiring board (see figure 7, left).

a)

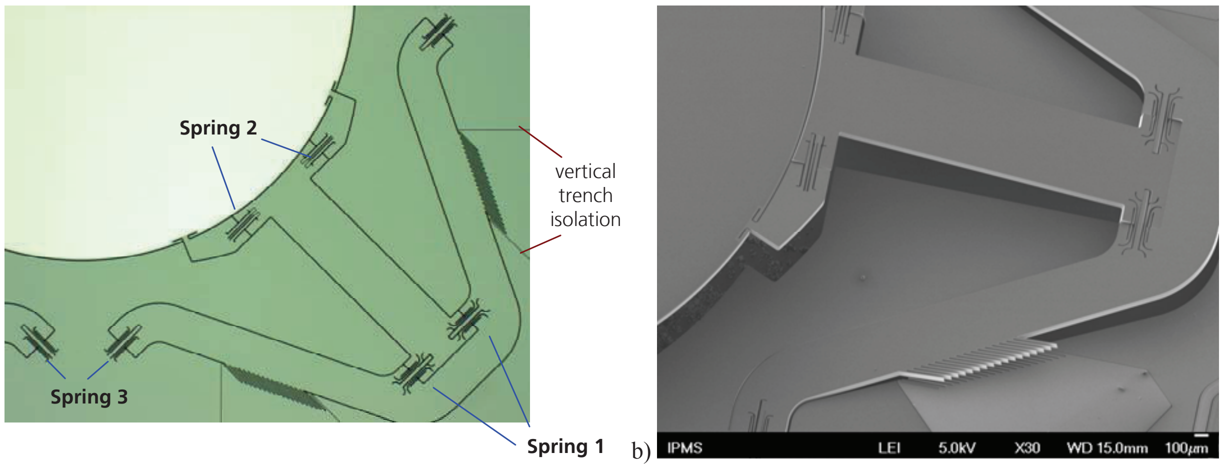

Figure 2: Photographs of four pantograph suspension; un-deflected (a) and SEM of 400 µm pre-deflected translatory MEMS (b).

2.3 Experimental results

The frequency response behavior of the translatory MEMS devices have been measured by means of a MICHELSON interferometer setup [2]. The devices were measured with a down frequency sweep at varied driving voltages and pressures. To vary the ambient vacuum pressure the MEMS sample under test was encapsulated in a small vacuum camber. In the experimental setup the vacuum pressure could be varied from ambient pressure down to 10 Pa as the minimum. The translatory MEMS devices are driven in open loop operation [2] with a pulsed driving voltage of 50 % duty cycle and a pulse frequency twice the mechanical oscillation. The experimental results of translatory MEMS (1st prototype design) with large mirror diameter of D = 5mm is exemplary shown in figure 3.

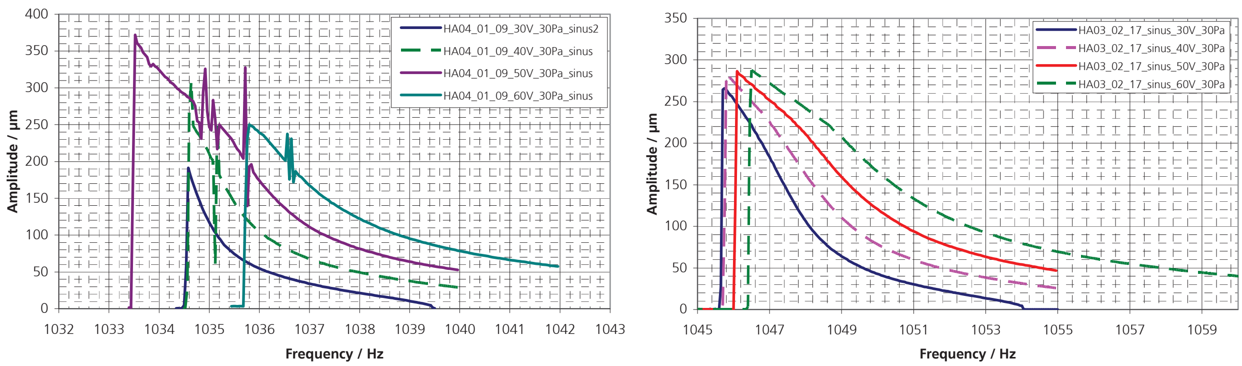

Figure 3: Experimental results of translation MEMS with D = 5mm (1st prototype); pulse frequency response curves measured for varied driving voltages under vacuum conditions of 30 Pa (left); Experimental issues of 1st prototypes are obvious to be eliminated by redesign: (left) regions of instable oscillation (driven with pulse voltage), (right) stiffening effect.

For the translatory MEMS with 5mm mirror diameter a amplitude of maximal ± 300 …370 µm was measured at a vacuum pressure of 30 Pa and a driving voltage of U = 60 V. Hence, for this MEMS device the FTS specification of at least ± 500 µm amplitude was not achieved at minimum pressure of 30 Pa due to higher viscous damping, where no oscillation occurs in normal ambient even for larger driving voltages of up to 100 V. In addition several experimental issues were observed at larger deflection > 200 µm like regions of instable oscillation (see figure 3a) and stiffening effect. The reason is assumed to be related to Eigen modes of the pantograph levers. The regions instable oscillations within the frequency response curves could be significantly reduced by using a pure harmonic driving voltage of twice the oscillation frequency instead of a square wave. Hence a redesign was required for the 5mm translatory MEMS mirror to reduce damping and to eliminate parasitic effects.

In contrast to the results of the 5 mm mirror device the alternative translatory MEMS device with slightly reduced mirror diameter of D = 4.2 mm have shown an improved overall performance. The frequency response curves measured at 30 Pa and varied driving voltages are shown in figure 4 (left). Here, continues increase of amplitude and reduced resonance frequency is obvious for increased driving voltages - as expected from the dynamic simulations. Typically, an amplitude of ± 500 µm was achieved at driving voltages of U = 70…80 V at minimal pressure of 30 Pa. Amplitude of ± 700 µm was measured as the maximum. No parasitic oscillations were observed within the specified amplitude range of ≤ ± 500 µm. In addition the dynamic tilt error of the oscillating MES device estimated to 10 arcsec using a stroboscopic autocollimator setup. The dynamic mirror deformation – which is maximal at the turning points of mirror oscillation – was simulated to $\delta_{p\text{-}p}$ = 220nm (λ/11.4). Hence, beside the slightly reduced mirror diameter of 4.2 mm the full specification required for a miniaturized FTIR spectrometer as successfully achieved for this alternative design of a large stroke translatory MEMS device. Figure 4 (right) shows the pressure dependency of frequency response measured at 70 V for a 4.2 mm translatory mirror device. Here, vacuum pressure was varied between 20….1000 Pa. For the 4.2 mm mirror a reduced damping was measured, but also no oscillation occurred in normal ambient. To achieve the full amplitude of ± 500 µm a vacuum of ≤ 50 Pa and 70…90 V driving voltage is required.

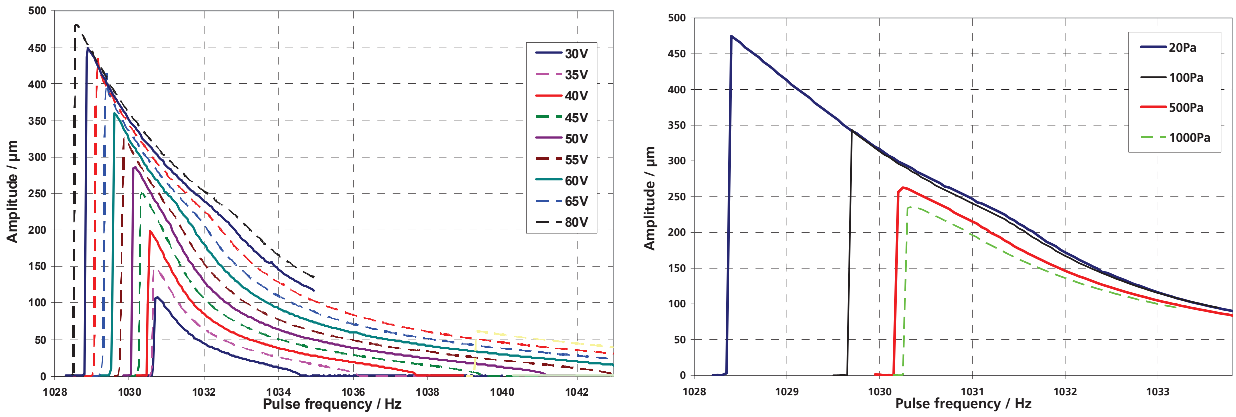

Figure 4: Experimental results of translation MEMS with reduced mirror size of D = 4.2 mm (1st prototype); pulse frequency response curves measured for varied driving voltages under vacuum conditions of 30 Pa (left); frequency response for varied vacuum pressure measured at 70 V pulse voltage.

2.4 Optimization of large stroke MEMS design

Beside the general specifications of MEMFIS the redesigned MEMS devices should avoid the issues of 1st translatory MEMS demonstrators with 5mm mirror diameter:

- Avoiding of any parasitic oscillation by improvement of mode separation of pantograph mirror suspension, supposed to be responsible of shown reliability issues,
- Realization of full translatory amplitude z_{max} = ± 500 µm also for a large mirror diameter of 5mm. Therefore damping of the oscillating translatory MEMS device at constant ambient pressure has to be reduced by reducing size and area of moving parts of the pantograph mirror suspension.

In figure 5 the geometry of the optimized translation MEMS device (2nd prototype with D = 5mm) is shown in comparison to the previous 1st prototype MEMS device. A significant smaller geometry of the pantograph levers is obvious for the optimized MEMS design (2nd prototype). The size reduction was realized by increasing the torsional deflection of the spring suspensions enabling the same stroke using a larger transformation factor of torsion to translation. Due to the smaller size and area of the pantograph suspension a significant reduction of viscous gas damping is expected. In addition due to the more compact pantograph geometry a larger driving capacity and improved driving efficiency could be realized.

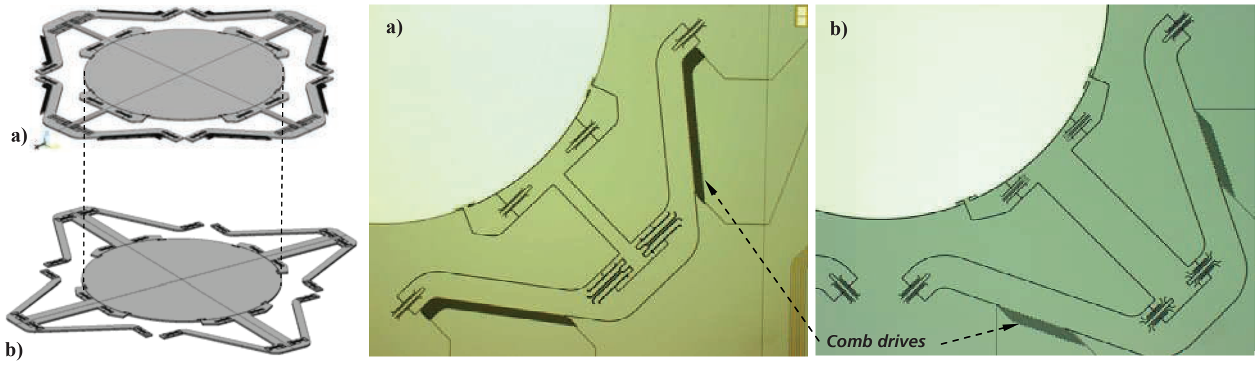

Figure 5: Optimized translation MEMS device (a) - 2nd prototype with D=5mm & stroke of 1mm in comparison to (b) 1st prototype device, the smaller pantograph lever design (a) enables reduced damping and higher driving efficiency.

2.5 Experimental results of optimized MEMS design

In figure 6 the experimental results of the optimized translation MEMS devices (2nd prototype design) with 5 mm large mirror diameter is shown. The frequency response measured for varied driving voltages under vacuum conditions of 30 Pa is shown in figure 6 (left) for a driving by means of the stationary comb electrodes. A significant improvement of the frequency response behavior is obvious in comparison to the 1st prototype device with D = 5 mm (see figure 3). Also significant larger amplitudes of typically ± 500 µm (up to ± 600 µm, see figure 6, left) could be measured at same pressure of 30 Pa for reduced driving voltage of U = 50 V in comparison to only ± 300 …370 µm @ U = 60 V enabled for the 1st prototype device (see figure 3). In addition, no issues with parasitic oscillations or stiffening effects were observed for the optimized MEMS design. Figure 6 (right) shows the influence of vacuum pressure on amplitude response measured at 40 V driving voltage. A significant lower damping and driving voltage is obvious. In contrast to the 1st prototype design the optimized MEMS design enables also an oscillation in normal ambient. Even for 5mm mirror device ± 80 µm amplitude were measured in normal ambient at 40 V and ± 460 µm at 30 Pa. Hence, the optimized translatory MEMS devices enable a reduced effort for vacuum package due to the significant lower damping & driving voltage.

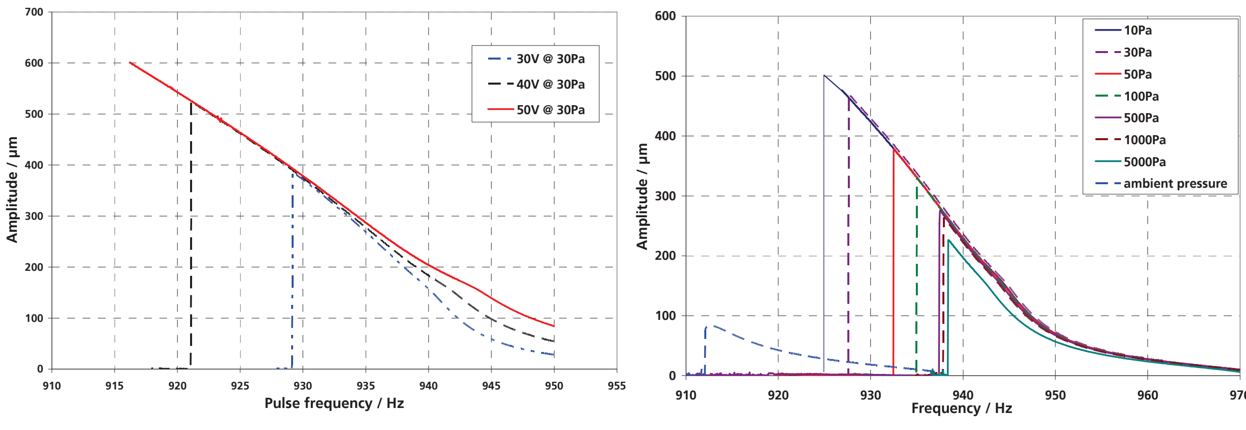

Figure 6: Experimental results of optimized translation MEMS with D = 5 mm & stroke of 1mm (2nd prototype); frequency response curves measured for varied driving voltages under vacuum conditions of 30 Pa (left) driven by movable comb electrodes; pulse frequency response of translatory MEMS measured at 40V driving voltage and varied vacuum pressure.

3 Outlook

The large stroke translatory MEMS devices, presented in this paper, will be used to build an improved version of a miniaturized MEMS based FTIR spectrometer [2]. The system concept is based on a miniaturized conventional optical Michelson setup combined with the new translatory MEMS devices used for optical path length modulation (see figure 7).

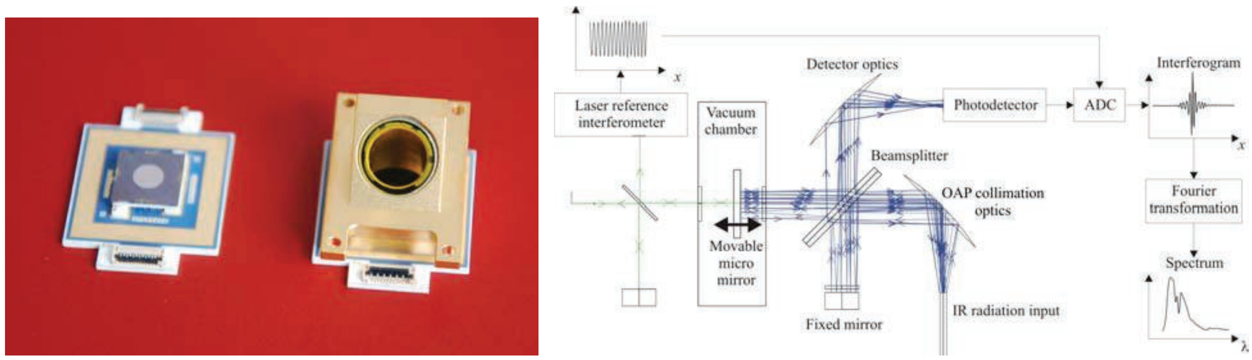

Figure 7: Optical vacuum package of translatory MEMS (left); Miniaturized MEMS based FTIR spectrometer, optical layout and block diagram of the signal path.

To guarantee the full typically ± 500 µm amplitude a long term the MEMS component has to operate in vacuum of < 50 Pa us discussed before. Hence, the MOEMS device has to enclose into a sealed optical vacuum package so that the external vacuum supply used in the first FTS prototype [1] will become obsolete. Currently, an optical MEMS vacuum package is under development especially designed for a broad IR spectral range (λ = 2.5 µm…16 µm). The optical vacuum package is based on a hybrid chip assembly using a ceramic wiring board and hermetic soldering of ZnSe window and metal can housing (see figure 7). It has been shown in this paper that the requirements for optical vacuum packaging can be significantly reduced by using a optimized MEMS design with reduced gas damping. The experimental results of optical vacuum packaging and final system integration into a miniaturized FTIR spectrometer will be published elsewhere sonly. These actual developments should lead to a sensitive, reliable and easy to use stand alone FTIR spectrometer qualified for industrial applications e.g. process control.

4 Conclusions

In this paper we present a resonant driven translatory MEMS mirror enabling extraordinary large stroke of up to 1 mm for optical path length modulation. Due to an optimized mechanical design using four pantograph suspensions of the 5 mm large mirror plate previous problems with mode separation could be solved. Now, the new translatory MEMS actuator can provide a precise out-of-plane translation of ± 500 µm amplitude in vacuum of 50 Pa, typically. A significant lower damping could be realized for an optimized MEMS design were larger torsional spring deflections are used to enable a more compact pantograph geometry. Experimentally up to 1200 µm stroke @ 30 Pa & 50 V were achieved even for a 5 mm aperture. Now also an oscillation in normal atmosphere was realized, so fare ± 80 µm were measured in normal pressure at only 40 V.

The new translatory MEMS devices are very promising for miniaturized FTS, to replaces expensive, complex and shock sensitive drives. The versatility and ruggedness of a MOEMS based FTS makes it ideal for process control and applications in harsh environments (e.g. surveillance of fast reactions due to the high scan rates). This enables a completely new family of low cost handheld FTIR analyzers with a spectral resolution of up to 5 cm^{-1}, 1000 scans/s and SNR > 1000 e.g. applied by individuals for ad-hock inspection of food or environmental parameters.

We acknowledge financial support by the European Commission in context of the FP7 project MEMFIS.

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