High resolution miniature FTIR spectrometer enabled by a large linear travel MEMS pop-up mirror

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Abstract

This paper reports the design, fabrication, and characterization of a millimeter diameter, surface micromachined Micro-Electro-Mechanical-Systems (MEMS) mirror, which is assembled perpendicular to the substrate and can be linearly and repeatedly traversed through 600 μm. The moving mirror, when combined with a fixed mirror and beamsplitter, make up a monolithic MEMS Michelson interferometer; all are made on the same substrate and in the same surface micromachined fabrication process. The beamsplitter has been specifically designed such that the motion of the mirror enables modulation of light over the 2-14 μm spectral region. The rapid scan MEMS Michelson interferometer is the engine behind a miniaturized, Fourier transform infrared (FTIR) absorption spectrometer. The FTIR measures the absorption of infrared (IR) radiation by a target material, which can be used for the detection and identification of gases, liquids, or solids. The fabrication of the mirror with the ability to displace 600 μm along the optical axis enables the miniaturized system to have species identification resolution, while leveraging wafer scale batch fabrication to enable extremely low system cost. The successful fabrication of the millimeter diameter mirrors and beamsplitter with interferometric alignment over the range of travel of the moving mirror promises unprecedented sensitivity relative to the size of the FTIR spectrometer system.

Keywords: Fourier transform infrared spectrometer, FTIR, MEMS, Michelson interferometer, 3D assembly

1. Introduction

Block MEMS, LLC launched a scientific war on terror with the real and practical application of broadband IR absorption spectrometry to counter chemical warfare. It aimed to build a cost-effective, broadband IR absorption spectrometer, dubbed "ChemPen™," with sufficient spectral resolution to detect and identify toxic chemical gases deployed by enemy agents or terrorists. After three years of experimentation and detailed analysis, Block MEMS identified significant cost challenges in the traditional construction of a miniature Michelson FTIR and concluded that a cost-effective detection device could only be reasonably achieved via a monolithic construction of the Michelson core without external handwork or alignment. A Michelson interferometer is a complex mechanical device and places severe constraints upon the optical relationship between its components. Currently, few methods can achieve the required interferometric tolerances in a repeatable and reliable fashion, among them photolithography.

Spectral resolution requirements were considered first. Extensive experience with IR and Raman spectra and detection algorithms of toxic agents led to a practical engineering choice for these relatively heavy molecules at STP ambient. In the Michelson interferometer, resolution improves as the moving mirror increases its range of motion. Given the desired spectral resolution, 8cm^{-1}, and some margin in the design, a peak-to-peak travel of 600μm was implemented—an unprecedented distance for MEMS mechanical motion.

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Because this device could only exhibit moderate sensitivity due to its size, the ChemPen™ design accommodated the maximum mirror sizes, consistent with the required flatness and tilt. (Other ancillary techniques for improving system sensitivity are continuously under investigation). The original ChemPen™ design specified 0.5 mm clear apertures. Sensitivity based on that size was calculated, and ChemPen™ would be able to see 6 mg/m^2 (1 ppm-m) concentration of SF_6 in one second, with a signal/noise of 1:1, at room temperature. This parameter is called the Noise Equivalent Absorbance (NEA). More recent advances in planned MEMS scale pre-concentrators and in improved semi-cryogenic detectors—to be discussed in future papers—have substantially improved the predicted sensitivity. Early experiments indicated that the required flatness and tilt specifications could be achieved with 1 mm clear aperture mirrors. This alone improves the sensitivity by a factor of four, lowering the NEA, and yields predicted native sensitivities of 250 ppb-m of SF_6 in one second.

The typical spectral range utilized for the C-Agents is 8-13μm, particularly in standoff measurements with 300 K ambient as the source. ChemPen™'s absorption system utilizes a much hotter source (1100 K) and creates sufficient photon flux to obtain good spectra down to 2 μm in the absorption configuration, greatly facilitating the identification of many Toxic Industrial Chemicals (TICs) and propellants. Research in absorption spectra with known standards and concentrations is currently ongoing, and results will be published when appropriately verified.

2. MEMS Michelson Interferometer

The current MEMS embodiment of a Michelson interferometer is shown in Figure 1. There are three optical components (stationary mirror, moving mirror, and beamsplitter), which define two distinct beam paths in the interferometer. All components are essentially identical in their construction, though the beamsplitter is elongated by $\sqrt{2}$ to account for the 45° angle of incidence; each has a primary mirror component which is an optical surface of interest, secondary components that hold the primary components in place to maintain their interferometric alignment, and proprietary self-locking mechanisms that enable irreversible assembly. The beamsplitter has been specifically designed such that the motion of the mirror enables modulating light over the 2-14 μm spectral region (Figure 2).

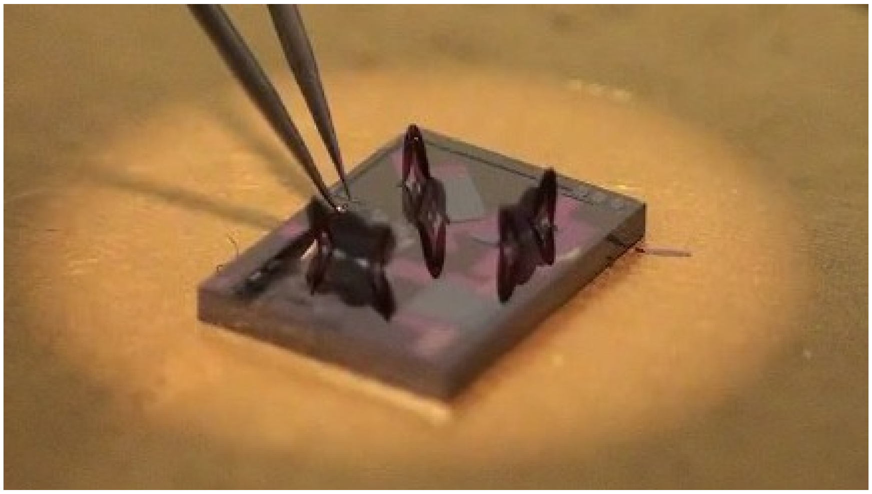


Figure 1. World first monolithic MEMS Michelson interferometer, which is being tested with two probes shown

The MEMS engine behind the ChemPen™ is made in the SUMMiT-V fabrication process at Sandia National Laboratories, Albuquerque, NM[1] and consists of five layers of polysilicon, with intermediate sacrificial oxide between each polysilicon layer, and specific features enabling rotating members with less than 0.25 μm clearance. Post-processing consists of bond pad and trace metallization, dice, critical point dry, and mirror metallization post release to minimize a change in curvature of the fixed and moving mirrors. ChemPen™ is currently assembled manually[2], though batch assembly techniques are under development.

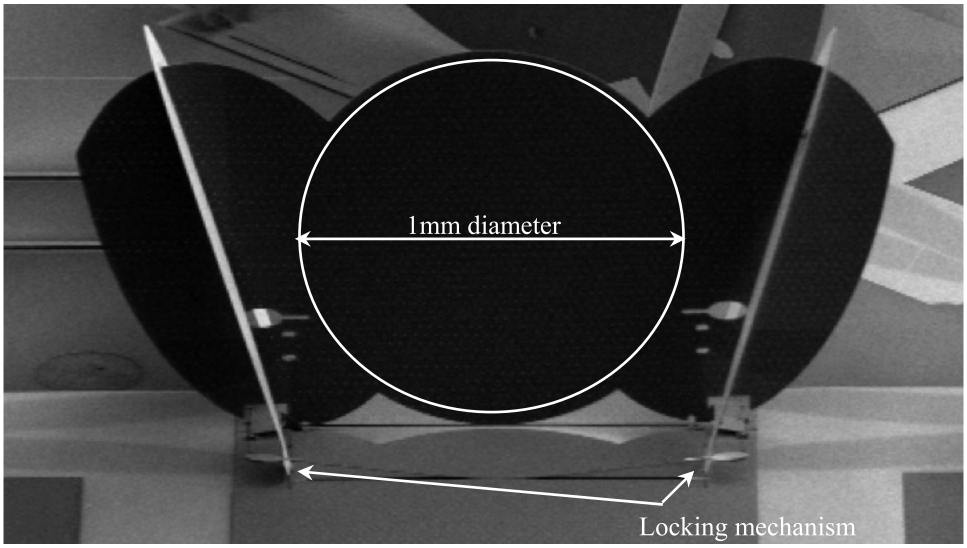


Figure 2. SEM Micrograph of a 1 mm clear aperture, reflective mirror component with proprietary self-locking mechanism

3. Characterization

3.1 Optical quality

In order to achieve the required reflectivity in the mid-to-far infrared spectral region, both stationary and moving mirrors need to be coated with a substantial amount of metal, specifically gold (Au). In the past, two major technical challenges with typical wafer-scale mirror metallization were identified prior to release and following release in hydrofluoric acid (HF): (1) substantially increased mirror curvature due to additional residual stress associated with the necessary adhesion promoter, and (2) electronic galvanic corrosion, where an electrode potential difference between gold and polysilicon in aqueous HF yields preferential corrosion of polysilicon mirrors, which creates significant structural instability and enlarged grain structures[3].

In response to these challenges, an alternative, post-release metallization technique was developed and utilized in ChemPen™ that eliminates the use of highly stressful adhesion layers and furthermore provides a fundamental solution to the electronic galvanic corrosion. Precisely aligned batch-scale metallization was achieved using a custom built shadow mask assembly, which allows repeatable, sub-μm level alignment between the top shadow mask and base plate via kinematic couplings[4]. Figure 3 illustrates metalized reflective mirror components prior to assembly.

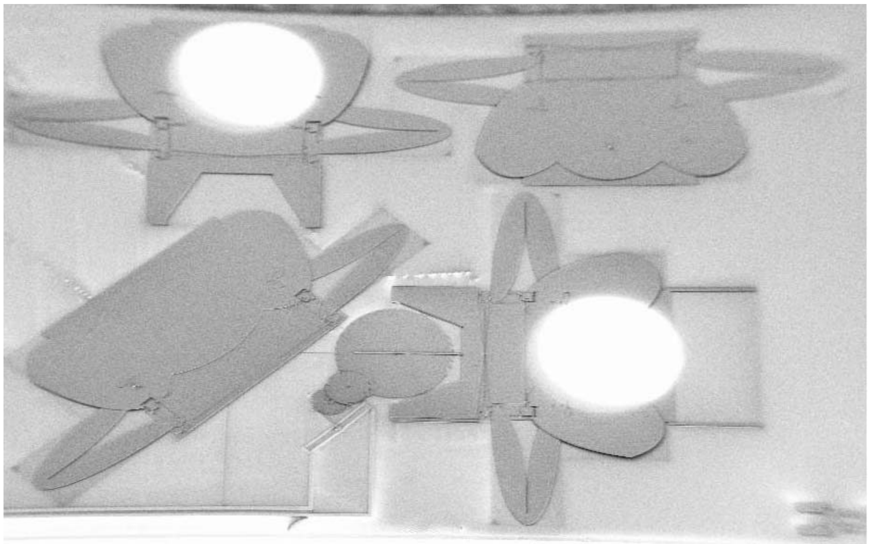
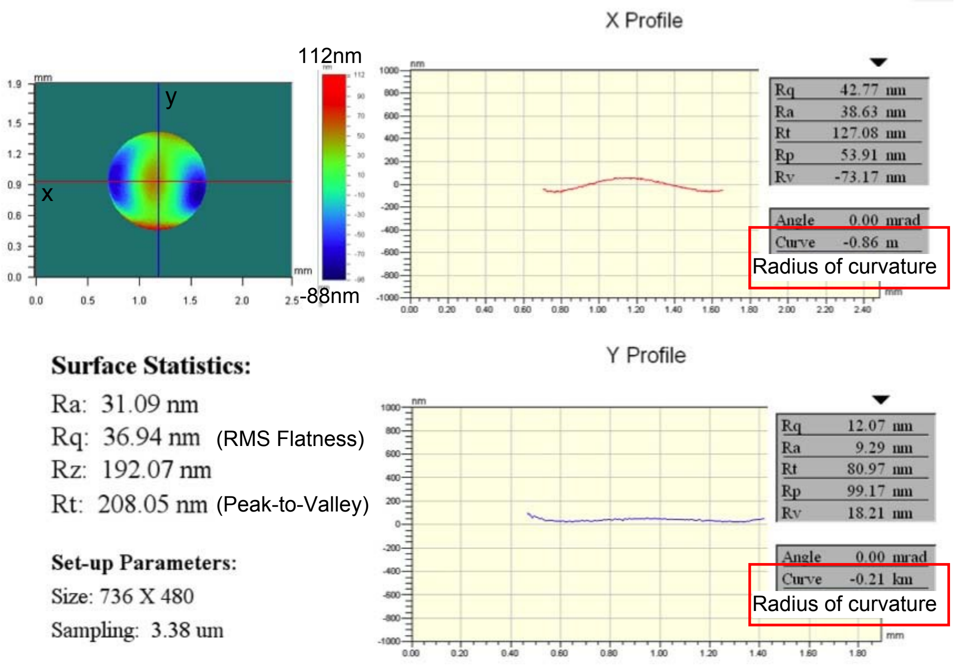


Figure 3. Metallized MEMS Michelson interferometer module prior to assembly

The surface topography of the metalized and assembled mirrors was measured using an interferometric contour microscope (WYKO, NT 2000). Combining post release metallization with various mirror stiffening techniques of the metal coated structures resulted in a substantial improvement in RMS flatness and an increased curvature radius, when compared to previously recorded data. Less than 40 nm of RMS flatness was measured over the entire clear aperture, which corresponds to less than λ/50 of the minimum operating spectral region of 2 µm. A peak-to-valley difference of less than 210 nm was achieved, resulting in a curvature radius greater than 80 cm and only 2µm–considerably less than one fringe—across the entire clear aperture. The developed process is robust and highly repeatable.



Surface Statistics:

Ra: 31.09 nm
Rq: 36.94 nm (RMS Flatness)
Rz: 192.07 nm
Rt: 208.05 nm (Peak-to-Valley)

Set-up Parameters:

Size: 736 X 480
Sampling: 3.38 um

Figure 4. Measured surface topography of metallized and assembled mirror segment

3.2 Mirror motion

ChemPen™ is designed to achieve better than 8 wavenumber (8 cm^{-1}) resolution, which requires an unprecedented, 600 µm physical mirror displacement. Such large travel is achieved by a combination of the thermal actuator system attached to a large gear and crank system. The innovative thermal actuator was developed jointly with Sandia National Laboratories[5]. The thermal actuator's pawl arm engages the ratchet teeth of the clocking gear wheel, thereby rotating the clocking gear with each thermal cycle (pulse) of the actuator. The clocking wheel then engages the crank-shaft gear, which has an associated connecting rod attached at a specified point to create a 600 um diameter circle. The connecting rod linearly displaces the platform, which is constrained by linear rails. The platform geometry is configured in a 2:1 (length/width) aspect ratio to provide improved linearity of travel, while reducing the potential for mechanical binding from the guiding mechanism (Figure 5).

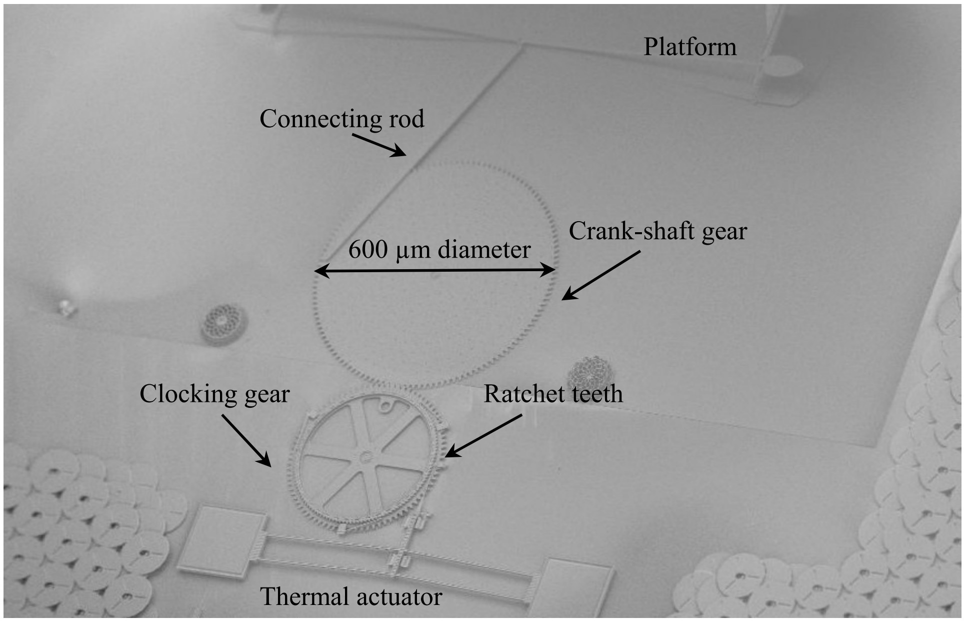
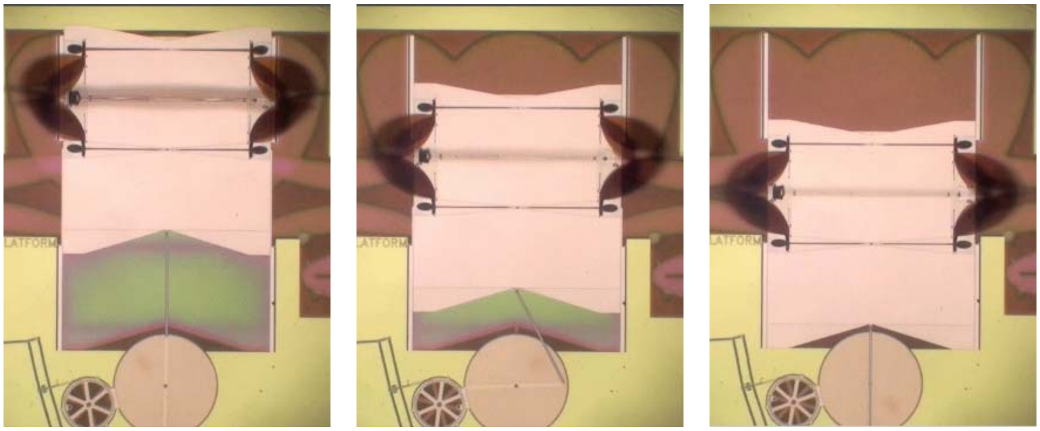


Figure 5. SEM Micrograph of components that enable unprecedented 600 um mirror motion



(a) *(b)* *(c)*

Figure 6. Nomarski microscope pictures of the moving mirror in action
(a) The moving mirror is at the farthest point from the actuator; (b) The moving mirror is half way to the actuator as the gear rotates clockwise; (c) The moving mirror is at the closest to the actuator and at the end of its motion

The thermal actuator was operated at approximately 200 clicks per second resulting in one full cycle of the mirror in just over one second. The motion of the moving mirror was investigated in detail with a single point laser vibrometer, which consisted of a laser interferometer head (KEYENCE, LK-G32) and its controller unit (LK-G3001). This instrument allows displacement measurements over a ±5 mm range with a position inaccuracy of less than 50 nm. The data set in Figure 7 represents over 4000 points during one cycle of the mirror. The step size follows a sinusoidal pattern and is largest near the zero displacement point, while approaching zero at both ends of the travel range. A separate set of measurement shown in Figure 7 represents transient time response analysis (i.e. the step response) between gear clicks. Upon receiving an input signal (i.e. gear click), the rise time of the step is 1 msec and the response settles quickly, which indicates that this is a near-critically damped system. A peak-to-peak value of 83 nm was measured in the settled region.

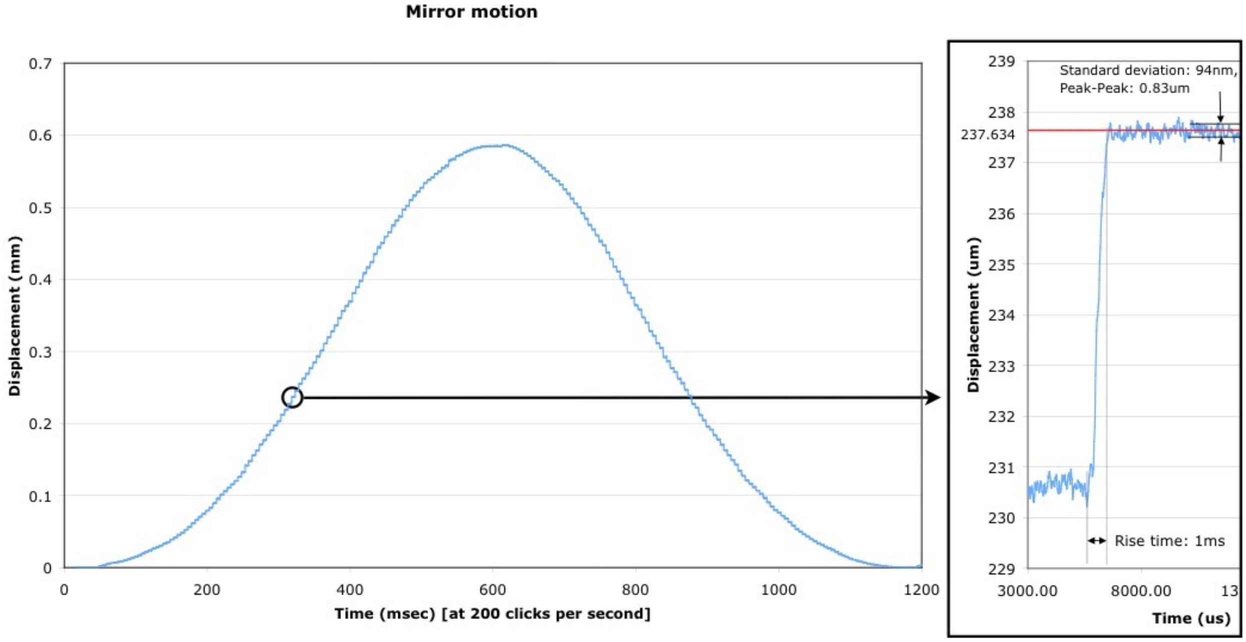


Figure 7. Plot of mirror motion as a function of actuation time;
approximately 225 clicks of the thermal actuator complete one full cycle of the mirror.

Maintaining alignment precision during mirror actuation is a substantial challenge in MEMS, since such large displacement is typically at the expense of reduced positioning precision. A number of proprietary platform guiding techniques were developed for ChemPen™ that constrain platform motion tilt to within interferometric tolerances. A custom apparatus with a He-Ne laser was then used to characterize the dynamic alignment of the entire system, specifically the measured tilt during actuation. First, the He-Ne laser is directed onto individual moving mirror surfaces or full interferometers. The output laser beam reflects off the assembled MEMS mirror and travels 1.6 m to amplify and measure small angular deviations of the MEMS mirrors. A CCD camera at the image plane of the apparatus captured a series of images over several actuation cycles of the MEMS Michelson interferometer for subsequent computer image processing.

The software developed uses a low pass filter to clarify the image, followed by a centroid calculation in each frame of the images that calculates the angular deviation of the optical beams. Images were then batch processed to calculate the maximum amount of tilt in both vertical and horizontal directions. The MEMS achieves less than 0.1º (6 arc minutes) in vertical and 0.03º (1.8 arc minutes) in horizontal tilt error with its proprietary guiding mechanism. These results demonstrate sufficient sensitivity in the spectral region of interest.

3.3 Interferometric alignment

To assess the interferometric alignment of the MEMS Michelson interferometer, a second testing apparatus with a He-Ne laser was configured. While a mirror was in continuous operation, traversing 600 µm from peak to peak, the resulting dynamic interferograms resulting from the interferometer were recorded using a CCD camera and image collecting computer system. Two static frames of precisely aligned interferograms taken from the dynamic interferogram video are shown in Figure 8. Since even the shortest operating wavelength in the region of interest (i.e. $\lambda = 2.5\text{-}14$ µm) is substantially greater than the He-Ne laser used in this experiment (i.e. $\lambda = 633$ nm), this result promises further improved modulation depth in the mid-to-far infrared spectral region, which improves instrument sensitivity.

One can model and simulate the Modulation Depth (or Modulation Efficiency = M.E.) expected for each type of imperfection in the optical components, but given the static interferograms shown below there would be $2.5/0.633 \approx 4$X fewer fringes across the image at 2.5µm and even fewer at the longer operating wavelengths.

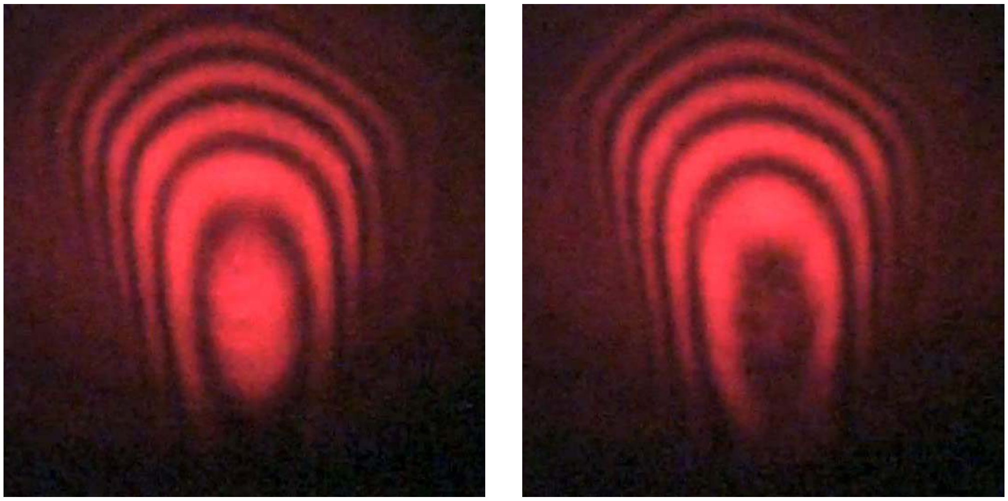


Figure 8. Two images from a dynamic interferogram pattern video taken over several actuation cycles of the Michelson interferometer; note central bulls eye difference representing approximate quarter wave of motion (0.633µm/4) along the optical axis

4. Conclusion

ChemPen™ successfully demonstrated a monolithic MEMS Michelson interferometer with 8 cm^{-1} resolution capability and its preliminary system level results shown above. Significant contributions to the existing MEMS state-of-the-art designs include innovative 3-D self assembly structures enabling interferometric alignment of three, one millimeter diameter, clear apertures monolithically on one substrate, and an unprecedented 600um mirror motion while maintaining its interferometric alignment. ChemPen™'s success opens a new, revolutionary path to a highly sensitive and cost-effective miniaturized FTIR system.

Acknowledgements

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