A novel method of creating a surface micromachined 3-D optical assembly for MEMS-based, miniaturized FTIR spectrometers

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Abstract

This paper describes design, fabrication, and characterization of a miniaturized, Fourier transform infrared (FTIR) spectrometer for the detection and identification of toxic or flammable gases. By measuring the absorption by the target material of IR radiation, unambiguous detection and identification can be achieved. The key component of the device is a micromachined Michelson interferometer capable of modulating light in the 2 – 14 µm spectral region. Two major technical achievements associated with developing a MEMS interferometer module are discussed: development of a micromirror assembly having an order of magnitude larger modulation stroke to approach laboratory instrument-grade spectral resolutions; and assembly of monolithic, millimeter-scale optical components using multi-layer surface micromachining techniques to produce an extremely low cost MEMS interferometer, which has an unprecedented optical throughput. We have manufactured and tested the device. Reported optical characterization results include a precisely aligned, static interferogram acquired from an assembled Michelson interferometer using visible light wavelengths, which promises a high sensitivity FTIR spectrometer for its size.

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

1. Fourier transform infrared spectroscopy

FTIR spectroscopy is a well-established technique for obtaining accurate, high-resolution infrared (IR) spectra of solid, liquid, and vapor compounds and mixtures. It is unique in that one obtains high spectral resolution while maintaining high sensitivity through the use of an optical interferometer, such as the one developed by Michelson[i]. Inherently high sensitivity can be traded for more rapid data acquisition or less expensive detectors. Their ability to capture complete spectra quickly offers advantages when interfacing with a gas chromatograph, mass spectrometer, or a pre-concentrator.

The spectrometer based on a Michelson interferometer works by splitting the incoming radiation beam into two components and causing them to optically interfere and modulate the output to the detector. This output waveform is termed an interferogram. Each incident radiation wavelength is modulated at a different frequency and hence can be extracted quantitatively from the resulting complex signal by performing a Fourier transform on the interferogram.

The high sensitivity of the interferometer, as compared with dispersive systems comes from two features. First, the interferometer collection optics can be much more efficient and they couple to a relatively large aperture in lieu of a narrow slit (Jacquinot[ii] or "throughput" advantage). Second, such an instrument looks at all wavelengths all of the time rather than just one or a few at a time, which wastes all the other non-observed photons. While this "multiplex" or Fellgett[iii] advantage

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can be achieved with a full array of staring detectors in the focal plane of a dispersive system, such arrays of detectors, which are sensitive and function over the 2 – 14 µm band are very expensive.

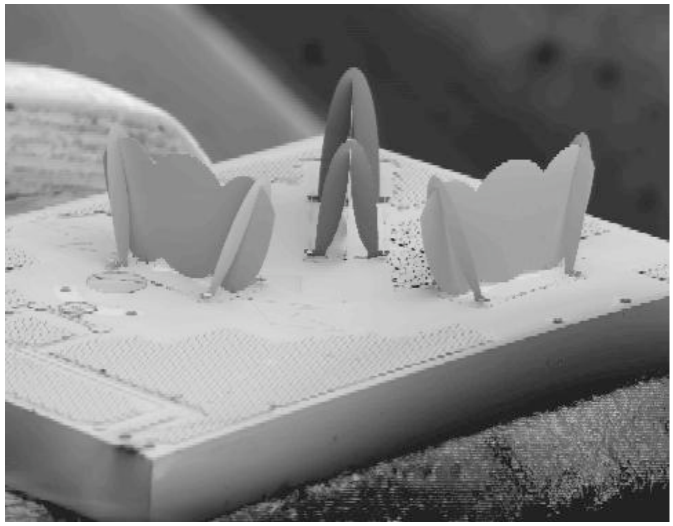

Figure 1. SEM micrograph of Michelson interferometer

Most Michelson FTIR systems require high precision optics and equally precise alignment and mechanical stability. Block MEMS, LLC, which has more than 45 years of experience developing such systems, is developing a microelectromechanical systems (MEMS) based Michelson interferometer whose alignment and high quality optics are built into the surface micromachined structures (Patents pending).

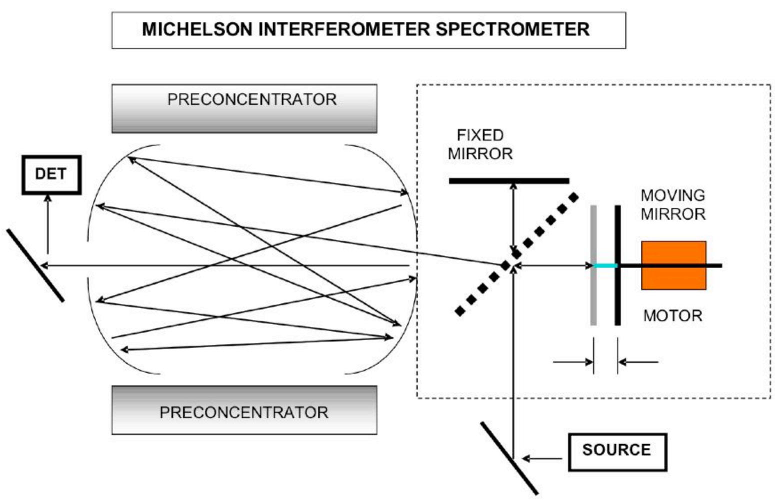

Figure 2. Schematic diagram of FTIR operating principle

The spectral recognition of individual compounds and even mixtures is a feature offered in most upscale FTIR laboratory systems. The software offerings from a wide variety of vendors will function in this MEMS device, as the spectral output is identical. Specialized recognition and alarm software with a restricted set of high priority target compounds is being developed for the military applications for individual war-fighter protection. A broader selection of toxic industrial compounds will be present in the libraries resident in instruments aimed at the first responder user.

2. Design and fabrication of Michelson interferometer

The design of a MEMS Michelson interferometer is based on a monolithic, lab-on-a-chip approach. This design scheme eliminates the use of external optics, which requires expensive, time-consuming interferometric alignment/curing methods. In contrast, multilayer surface micromachining, such as the five-layer SUMMiT-V[iv] fabrication technology, enables extremely low-cost manufacturing through batch fabrication.

Structures made by surface micromachining techniques inherently reside in the plane of fabrication, giving them essentially a two dimensional configuration. One challenge of device design however is the need for at least an order of magnitude larger modulation stroke in the reference arm of the interferometer, which precludes typical electrostatic actuation scheme in a surface normal direction.

To a first approximation, the sensitivity of a Michelson interferometer spectrometer system is proportional to the overall size of the optics. Nevertheless, it offers sensitivity advantage in the 2 – 14 µm IR spectral region to such an extent that even very small systems compare favorably with their dispersive counterparts: typical sensitivity advantage is several hundred to a thousand times over dispersive systems of corresponding size. While we are pushing MEMS in the opposite direction of general nano-themed trends—and toward larger structures—our design is further complicated by more stringent requirements on optical surface quality, flatness and perpendicularity.

Such technical challenges have motivated the development of an innovative, 3-D large optical components assembly described in this paper. Several 3-D assembly techniques have been reported previously. UCLA demonstrated the ability to fabricate optical structures, then assemble them out of plane to create elaborate optical systems on a chip, which in turn were commercialized into free-space photonics switches[v]. An early form of 3-D assembly was developed by UC Berkeley, which closely mimics flip-books[vi]. The Block MEMS design improves on all prior systems in terms of scale, interferometric alignment, and batch-assembly capability, thereby significantly improving optical performance and manufacturing cost.

Figure 3 shows the scanning electron micrograph (SEM) of assembled individual mirror structures. By applying an external force field, the primary mirror segment (primary) rises, followed by two assisting secondary components (secondary). The primary structure is the optical surface of interest which has a 1 mm clear aperture, while the secondary structures hold the primary in place and maintain the angular tolerance to enable interferometric alignment. The motion of the secondary displaces the tertiary locking features to engage and lock in place, achieving full irreversible assembly.

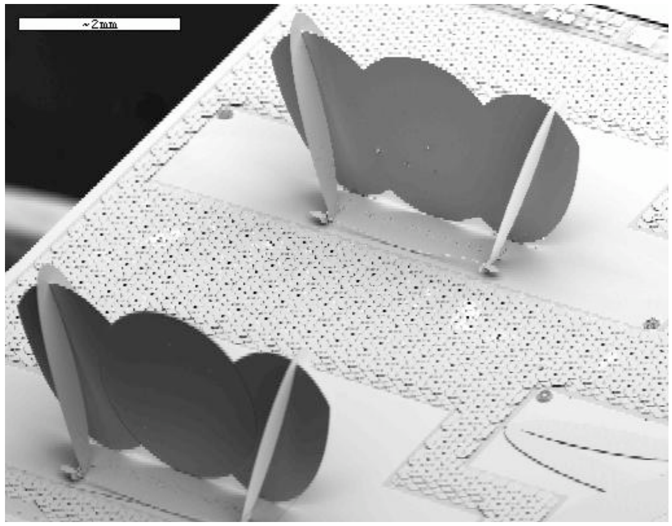

Figure 3. SEM micrograph of assembled, individual mirror segments

Each of these components, primary and secondary, rotates out of plane through the use of flexural hinges, which are constrained by the staple retainers. As opposed to typical pin-and-staple hinges allowing free rotation of structural components, flexure hinges behave as a torsion spring, so that each component is sprung against the angle-setting datum surface, in turn maintaining interferometric alignment of the system. In addition, the use of staple retainers prevents out of rotational axis movement and improves robustness of assembly (Patents pending).

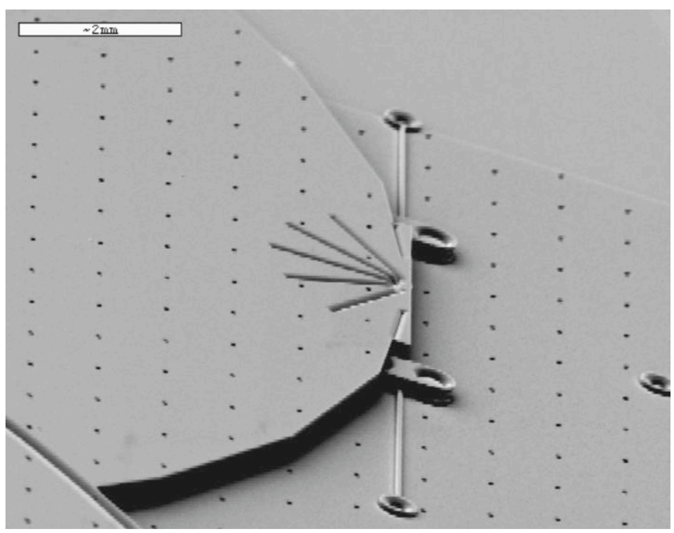

Figure 4. SEM micrograph of flexure hinges and staple retainers

A tertiary locking feature residing at the base of each side of secondary comprised of oval shaped locking tab head and a long tendon that attaches to the substrate at the other end. The length of tendon sets the final angle of the secondary. As the secondary rises, the locking tab head is displaced by a straight edge feature immediately underneath the oval head. The straight edge has a slit that fits the lateral dimension of the long tendon. As the straight edge rotates vertically, it eventually reaches an angular position that allows the locking tab to clear the straight edge and fall behind the secondary, causing the locking tab to drop into the slit, preventing further disassembly (patents pending). We have demonstrated self-assembly capability of our design using number of different methods including thermo-kinetic[vii], electrostatic, and centrifugal forces[viii]. In all experiments, the MEMS structures actively aligned to the field/force lines to displace locking mechanisms, promising batch-assembly of Michelson interferometers.

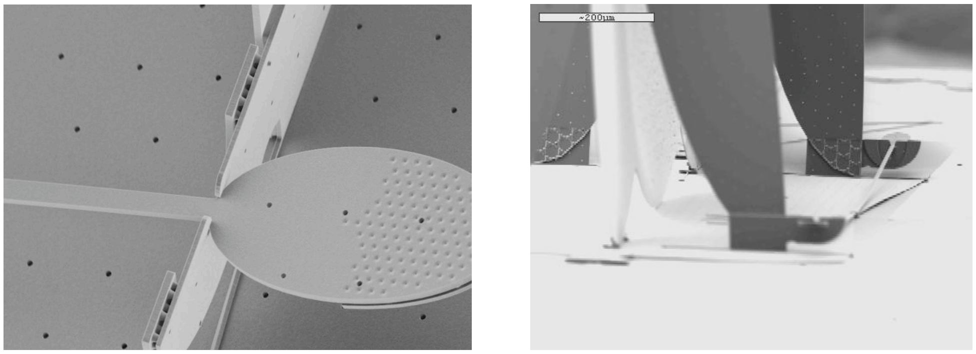

Figure 5. SEM micrograph of locking features
Left: Oval shaped locking tab head in slit, Right: Tendons residing at the base of secondary

The Block MEMS FTIR prototype is designed to achieve instrument grade resolution, specifically eight wavenumber (cm^{-1}) resolution. This specification requires a 500 μm moving mirror displacement while maintaining interferometric alignment during the entire excursion.

This is a substantial challenge in MEMS, since such large displacement is generally traded for less positioning precision. Traditional spring mechanisms for displacement assistance, such as folded beam springs or A-frame springs, do not provide such long displacement in a given practical die size. In addition, necessary gaps and rubbing surfaces in mechanical joints result in positioning errors and reliability issues. It would therefore be impractical to achieve interferometric alignment precision without first developing an alternative guiding mechanism and minimizing such mechanical joints.

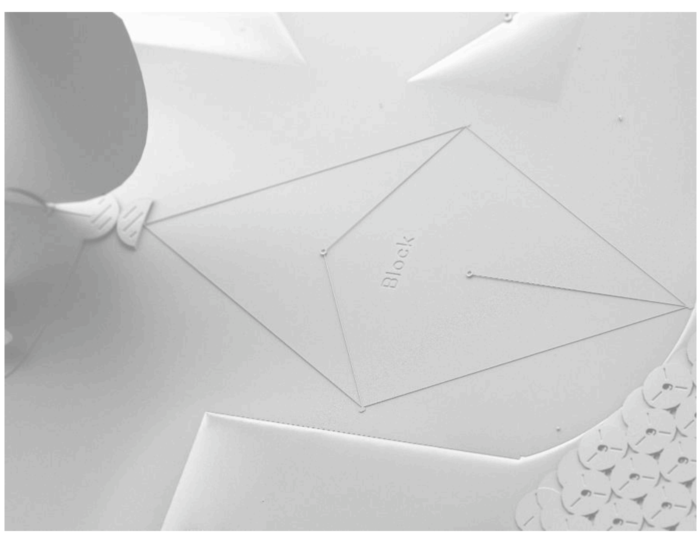

Figure 6. SEM micrograph of Straight-Line-Generator (Peaucellier linkage)

A mirror assembly was designed to be assembled on top of a movable platform to form the moving mirror of a Michelson interferometer. The platform is suspended by novel linkage systems, a MEMS implementation of an inverted Peaucellier linkage system. The endpoint of each linkage is constrained to trace a mathematically true straight line. By using linkages on both sides of the platform along with novel compliant joints[ix], allows larger angular motion without being subjected to the twisting moment across its range of travel, lateral positioning errors are efficiently compensated, restricting the platform to one line of travel.

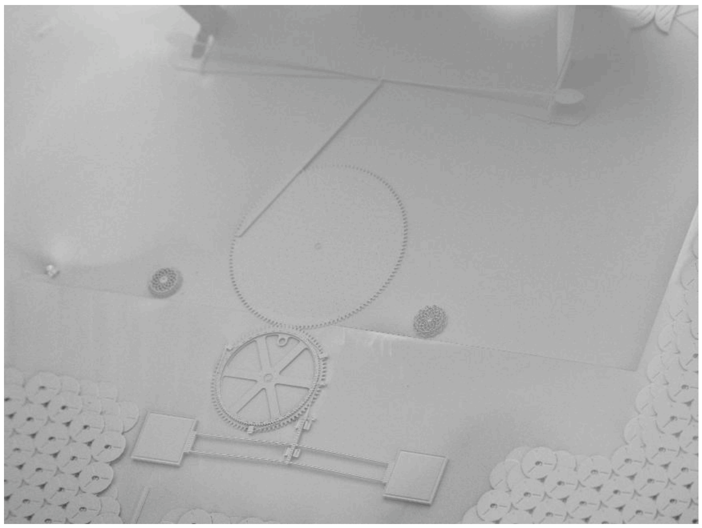

Figure 7. SEM micrograph of actuator and gear system

Platform displacement of 500 µm is achieved by the use of a thermal rotary actuator developed specifically for this system by Sandia National Laboratories. The drive system starts with a thermal actuator displacing a pawl coupled to a ratchet-geared clocking wheel. The thermal actuator provides orders of magnitude higher force output and improved displacement characteristic, while requiring lower actuation voltages than their electrostatic counterparts[x]. The clocking wheel rotates a crankshaft gear. As the crankshaft gear rotates, it pushes a connecting rod, converting continuous rotary motion into oscillatory linear motion—a combination that is the familiar piston/crank of internal combustion engines. The motion of the platform is efficiently constrained by the linkages. The system is configured to provide a linear, 500 µm displacement in discreet steps, though it can easily be altered to provide larger displacement. We have successfully demonstrated zero-skip actuation over millions of cycles, which promises a path to the ultimate goal of a greatly simplified open-loop mirror position control with exceptional reliability. The sinusoidal motion increments do not represent a fundamental mathematical problem as long at the maximum step size meets certain optical criteria which will be the subject of a separate paper.

3. Characterization results

Surface topography of assembled mirror components was examined to assess the optical quality. Individual dies were released in 49% HF solution and subsequently metallized using proprietary processes to achieve high reflectivity. Optical properties, such as peak-to-valley surface topography, radius of curvature, and RMS flatness errors were then characterized using a WYKO

NT2000 interferometric contour microscope. Each measurement was averaged multiple times in order to improve the measurement resolution.

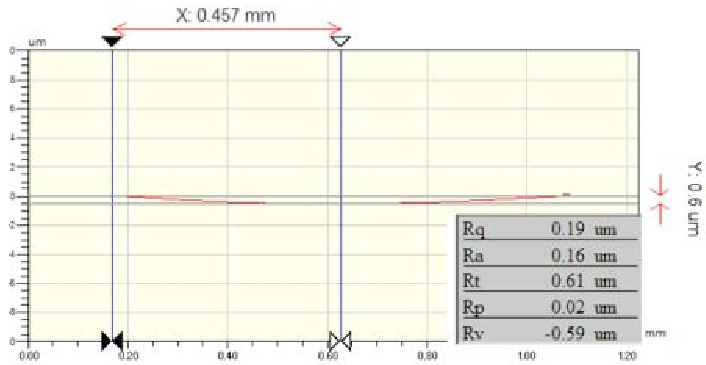

Figure 8. Surface topography of metallized mirror segment

An extremely flat and smooth surface was achieved over the entire 1 mm clear aperture with no visible structural or optical corrosion. Up to 15 MPa of residual film stress yielded 0.6 µm peak-to-valley surface topography, which correlates to over 20 cm radius of curvature. Less than 20 nm RMS flatness error corresponds to 1/100 of the minimum operating wavelength of 2 µm.

In addition to mirror flatness, perpendicularity of each erect mirror plays a fundamental role in achieving a high quality interferogram. A custom built apparatus to measure perpendicularity consisting of a He-Ne laser, pinhole, beam reflector, and a CCD camera was set up to characterize system perpendicularity. First, the relative distance of two output beams was recorded at an extended distance from the MEMS die to assess angular tilt of the Michelson interferometer mirrors. Next, relaying optics were placed at a distance from the die to amplify the resulting interference pattern; and any corresponding interferograms were recorded by a CCD camera. Both experiments were performed using fully assembled MEMS Michelson interferometers in the zero order position (i.e. zero path difference).

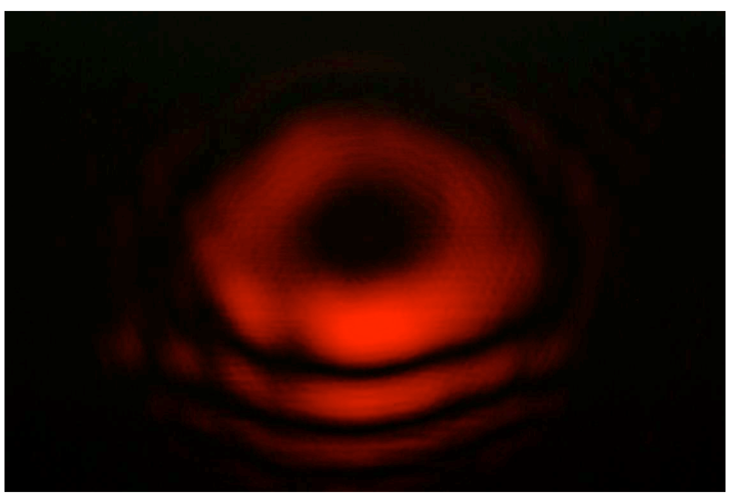

Figure 9. Acquired static Interferogram
from Block MEMS Michelson interferometer in zero path difference at 0.6328µm

Resulting angular tilt error of entire system was measured to be less than 12 minutes of arc, or 0.2°. A corresponding, precisely aligned interferogram was acquired with extremely high contrast. Since the wavelength of the light source used in the experiment was shorter than one-fourth of the shortest operating wavelength in our spectral region of interest, this result promises further increased modulation efficiency, which links directly to instrument sensitivity. Further overall alignment improvements are expected.

4. Conclusion

Technical achievements and challenges associated with manufacturing a surface micromachined Michelson interferometer are described. Using novel 3-D assembly techniques that were developed and implemented in this research, a manufactured and assembled Michelson interferometer demonstrates its feasibility to enable next generation, low-cost, high sensitivity FTIR spectroscopy. Future effort will focus on integrating manufactured Michelson interferometer into miniaturized FTIR spectrometers.

Acknowledgement

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