Magnetic actuated FR4 scanners for compact spectrometers

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ABSTRACT

A novel magnetic actuated polymer optical platform is integrated into a Michelson interferometer type Fourier transform infrared spectrometer. The proposed advantages of the novel platform over existing approaches, such as MEMS spectrometers, or bulky FTIR systems, include millimeter range dimensions providing a large clear aperture and enabling conventional machining for device fabrication, a controllable AC and/or DC motion both in rotational and translational modes, and low frequency operation. It has been demonstrated that the platform is capable of achieving 400 μ m DC deflection in ambient pressure in the translational mode, and a total optical scan angle exceeding 60 degrees in the resonant rotational mode. A Michelson type Fourier transform spectrometer was built using a retro-reflector bearing FR4 platform and a spectral resolution of 25cm⁻¹ is demonstrated with this setup. In addition, possible use of the same platform in various other spectrometer configurations and methods to improve the motion precision are discussed.

Keywords: FTIR, spectroscopy, FR4, Michelson interferometer, grating interferometer

1 INTRODUCTION

Infrared (IR) absorption spectroscopy is an established method for the detection and analysis of chemical and biological samples and is extensively used in a wide range of industrial and research applications. Conventional high resolution IR spectroscopy mostly utilizes FTIR systems, which are bulky, expensive and stationary equipment found in laboratory environment. FTIR spectroscopy could potentially be used for compact and portable sensors or analyzers, but current instrumentation, particularly the scanning mirror mechanisms, do not fulfill the requirements of a small and easy to use FTIR sensor. Such a compact and real-time operating analyzer could be used for monitoring the quality of gasoline at gas stations, the quality and consistency of products (e.g. food and drug industry), the safety in reaction environment, and countless other out-of-the lab applications. Hence, a number of compact IR spectroscopy systems, mostly using MEMS technology, have been developed. Schenk has developed a moving grating spectrometer using a torsional microscanner¹. A Michelson interferometer based FTIR spectrometer with a vertically moving resonant micromirror operating in vacuum was introduced by Kenda². Manzardo has developed a MEMS based lamellar grating based FTIR with 6nm resolution in the visible region³. The structure uses side walls of thick SOI wafers; however, surface roughness and side-wall thickness limitations imposes tight opto-mechanical tolerances and light collection efficiency limitations and requires the use of anamorphic optics for illuminating the thin and long mirror area. Our group has demonstrated a vertical comb actuator based lamellar grating interferometer with a wide travel range in ambient, good optical efficiency, and compact structure⁴. The MEMS component utilizes vertical resonant comb drives for actuation, light dispersion, and optical path difference monitoring. Correia, et al developed a 16 channel CMOS integrated Fabry-Perot spectrometer⁵ which is highly miniaturized but has lower spectral resolution compared the other methods listed.

In this work, we present a compact FTIR system in Michelson interferometer configuration, employing a novel electromagnetically actuated FR4 scanning platform. FR4 is a polymeric epoxy-glass resin commonly used as a substrate material for printed circuit boards (PCB) found in almost all electronics equipment. Therefore, the technology is widely available at low-cost. There have been numerous attempts at integrating new functionality into PCB technology^{6,7}. To our knowledge, our group was the first research to utilize FR4 as a platform to integrate electrical, mechanical, and optical functionalities^{8,9}. In this paper, we extend the use of this novel platform into FTIR spectroscopy. Dimensions of

the fabricated platforms vary in the millimeter range enabling conventional machining for device fabrication. Integrated electromagnetic actuation ensures a controllable DC and AC motion, avoiding the bulky and costly scanning mirror drive and control systems in conventional FTIR systems.

In Section 2, basic characteristics of the FR4 platform (material properties, mechanical structure etc) are discussed. A Michelson interferometer type Fourier transform spectrometer system is presented in Section 3 with experimental spectral measurement results. A brief discussion of other possible spectrometer configurations that can be implemented with the present platform is included in Section 4.

2 FR4 AS AN OPTICAL PLATFORM

2.1 Structural properties and fabrication

Figure 1 is a photograph of the FR4 movable platform carved from a printed circuit board with 250 μ m thick polymer and 35 μ m thick double-sided copper layers. On either side of the central 8mm by 8mm square plate, the copper layer is routed to form a coil. The plate is linked to the outer frame in a simple torsional scanners form through two flexure beams, which also carry the electrical feed-throughs for the coil (Figure 2). For optical functionality, two aluminum coated silicon mirrors are mounted on either side of the central plate. A permanent magnet placed underneath the FR4 scanner produce a DC magnetic field. An AC current flowing through the coils induces a Lorentz force (or torque) that moves the central plate in the desired mode. Depending on the orientation of the magnetic field and the direction of the current flow, the platform can be moved in torsional or translational or other oscillation modes.

Figure 1: Photograph of the conventionally machined FR4 scanning platform with and without the aluminum coated silicon mirror.

FR4, having a low Young modulus of about 20 MPa, is inherently a soft material and is a good candidate for low frequency scanning applications, which usually are very challenging for Silicon MEMS devices. Due to its stiff and brittle structure of crystalline silicon, low frequency (in the order a few hundred Hz) MEMS structures become very delicate and cannot survive the shock and vibration in the environment. The electrical circuitry required to drive the FR4 mechanical elements can easily be integrated on the same circuit board, using conventional PCB manufacturing equipment. A drawback of FR4 based mechanics as a result of conventional machining is the relatively low precision of the fabrication method compared to MEMS technology. The FR4 platforms presented in this paper have a minimum linewidth and spacing of 125 μ m for the coil and a minimum mechanical feature size of 500 μ m with a precision in the order of 100 μ m.

Figure 2: Schematic drawing of the platform with attached reflective mirror. Copper coils rest on either face of the platform.

2.2 Electromagnetic Actuation of FR4 scanners

FR4 platforms are actuated with electromagnetic force, allowing both DC and AC operation. A rectangular or circular permanent magnet is symmetrically placed underneath the platform creating a magnetic field $\mathbf{B}$. A current i passing through the coils under this magnetic field induces a mechanical force that vertically translates the platform. Figure 3 is a schematic drawing summarizing the actuation principle. On either side of the platform, lateral component of the magnetic field and the direction of the coil current are in opposite direction, creating a net force on the platform in the vertical direction. The vertical components of the field lines create lateral forces in opposite direction on either side of the platform that cancel each other.

Due to the large dimensions of the platforms, a significant amount of electromagnetic force can be generated by the actuators, leading to a large travel range, which is not easily achievable with MEMS structures. Depending on the orientation of the magnetic field and the direction of the current, the platform can be moved in a torsional or translational mode, making the device useful for various scanning applications.

Figure 3: Cross-sectional view of the electromagnetic actuator with a rectangular coil and circular permanent magnet that is symmetrically placed underneath. A current that pass through the coils induces a Lorentz Force of same direction and magnitude on either side of the platform, moving it in vertical (z) direction. Lateral Lorentz forces on either side cancel each.

3 FTIR SPECTROMETER USING FR4 PLATFORM

The FR4 platform investigated in the previous section was integrated into a Michelson type Fourier transform spectrometer as the movable mirror. A schematic drawing and a photograph of the built spectrometer are shown in Figure 4 and Figure 5, respectively. The movable mirror is the heart of such a system and the tolerances on motion precision are tight (i.e., the optical path difference along the clear aperture of the mirror should not exceed $\lambda/4$ where λ is the smallest measured wavelength). The FR4 scanners are fabricated via conventional machining; hence all corners of the mirror are not translated by the same, particularly for large deflections, resulting in significant distortion the acquired interferograms. Retro-reflectors are an effective solution for this problem, which are also widely used in bulk FTIR spectrometers to correct for mirror misalignments. Integration of thin and light-weight retro-reflectors onto the FR4 platforms to replace silicon flat mirrors drastically improved the maximum allowed travel range of the FR4 scanners at a cost of lower cone angle, due to their small aperture size.

Figure 4: Michelson Spectrometer configuration

Position feedback and sampling clock signal is obtained using the backside of a moving mirror and the fixed grating referred to as feedback grating. A visible laser diode (LD) at 1 in the visible band can be used to generate a non-linear sampling clock signal by using the zero crossing or the peaks of the photo detector (PD) signal. Accurate real-time sampling of the interference vs. OPD is a crucial requirement for interference-based spectrometers. Hence, an optical position feedback mechanism for the FR4 platform is implemented. The feedback system is essentially a lamellar grating interferometer with a monochromatic source placed at the backside of the mirror. As the mirror moves, the optical path difference of the grating is varied and the 0th order intensity is modulated. If the mirror velocity is constant, temporally uniform sampling of the interferogram ensures the spatial uniformity of the samples. However, in AC operation, due to the sinusoidal speed variation of the mirror, uniform temporal sampling of the interferogram corresponds to non-uniform spatial samples, on which Fourier transform is inapplicable. This is corrected by a special sampling and interpolation method. An elegant interferogram sampling method was developed by ¹⁰ in order to overcome the nonuniformity in the sampling intervals without introducing any delay for Fourier spectrometers that we adapted to and implemented for our system

Figure 5: Spectrometer Module. Reference mirror is mounted on a 6 axis micro-alignment stage

Experimental laser reference and interferogram data presented in Figure 6 are acquired with the aforementioned setup. For reference interferogram, a blue-violet laser diode (408nm) was used. For experimental simplicity, a red laser diode is used for the spectrum to be measured, instead of an IR source. Maximum travel range of the FR4 movable platform is 400 μm , yielding a spectral resolution of 25 cm^{-1} . Figure 7 shows the measured and the reference spectra computed from the data in Figure 6. The reference spectrum is computed from an ideal interferogram that would be obtained from a spectrometer with the same instrumental function. The travel range, which determines the resolution of the spectrometer, was limited by the wobbling of the platform, and can be increased with increasing magnetic field intensity of applied current.

Figure 6: Interferogram and laser reference obtained with the Michelson interferometer.

Figure 7: Experimental spectrum of a red laser diode. The reference spectrum is computed from an ideal interferogram that would be obtained from a spectrometer with the same instrumental function. Please note that both the reference and measured interferograms are apodized with a triangular apodization function.

4 DISCUSSION

Extension of the linear translation range of the platforms is essential to improve the performance of the spectrometer system. Current open loop operation of the platforms with a corner cube allows a travel range of half a millimeter without distorting the interferograms, but beyond this range, the mirror wobbling becomes a significant problem. The linear motion range of the scanner can be extended using multi-point position feedback and close loop-control using a back-emf sensor coil.

Depending on the orientation of the magnetic field and the direction of the current, the platform can be moved in a torsional or translational mode, making the device useful for various scanning applications. In the torsional mode, the FR4 platform can be used for a rotating grating spectrometer as in Schenk [1]. For this purpose, instead of a reflective mirror, a micro-molded, aluminum coated polymer grating should be placed on top of the FR4 scanner (9). The classical grating spectrometer employs a static grating and a detector array placed at the 1st diffraction order. For all wavelengths, 0th diffraction orders are at the same position; but 1st diffraction orders are spread in space due to different diffraction angles. The detector array then can be used to image the light distribution around the 1st diffraction order. In a rotating grating spectrometer, a single detector is sufficient, since as the mirror rotates, entire spectrum is scanned over the detector in time. For maximum light efficiency, a blazed grating should be used.

Figure 8: Rotating grating spectrometer with a blazed grating

5 CONCLUSIONS

A compact Fourier transform spectrometer in Michelson configuration is demonstrated using a vertically translating FR4 platform. An experimental resolution of 25cm^{-1} is obtained. Low frequency operation, long and controllable travel range, easy fabrication and easy integration are the major advantages of the proposed approach promising a great potential for development of compact spectrometer with good performance. Due to the flexibility of the actuation principle, the presented platforms can be actuated in different mechanical modes that can be used to implement other spectrometer configurations.

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REFERENCES

1. H. Schenk, H. Groger, F. Zimmer, W. Scherf, A. Kenda, "Optical MEMS for advanced spectrometers," *Proc. of the IEEE/LEOS conference on Optical MEMS*, p. 117-118, 2005.
2. Kenda, C. Drabe, H. Schenk, A. Frank, M. Lenzhofer, W. Scherf, "Application of a micromachined translatory actuator to an optical FTIR spectrometer," *Proc. of SPIE*, vol. 6186. 618609, 2006.
3. O. Manzardo, *et.al.*, "Miniature lamellar grating interferometer based on silicon technology," *Optics. Letters*, vol. 29, p. 1437-1439, 2004.
4. C. Ataman, H. Urey, A. Wolter, "A Fourier transform spectrometer using resonant vertical comb actuators," *Journal of Micromechanics and Microengineering*, vol. 16 pp. 2517-2523, 2006
5. J. H. Correia, M. Bartek, G. de Graaf, S.H. Kong, R. F. Wolffenbuttel, "Single-chip CMOS optical microspectrometer," *Sensors and Actuators*, vol.82, pp.191-197, 2000.
6. G. Van Steenberge, P. Geerinck, S. Van Put, J. Van Koetsem, H. Ottevaere, D. Morlion, H. Thienpont, P. Van Daele, "MT-compatible laser-ablated interconnections for optical printed circuit boards," *Journal of Lightwave Technology*, vol. 22, no. 9, pp. 2083- 2090, 2004.
7. B. S. Rho, S. Kang, H. S. Cho, H. H. Park, S. W. Ha, B. H. Rhee, "PCB-Compatible Optical Interconnection Using 45 -Ended Connection Rods and Via-Holed Waveguides," *Journal of Lightwave Technology*, vol. 22, no. 9, 2004.
8. H. Urey, S. Holmstrom, A. D. Yalcinkaya, "Electromagnetically Actuated FR4 Scanners," *Photonics Technology Letters*, vol.20, no.1, pp.30-32, 2008.
9. S. Holmstrom, A.D. Yalcinkaya , S. Isikman, C. Ataman, H. Urey, "FR-4 as a New MOEMS Platform," *The 7th IEEE LEOS Conference, Hualien, Taiwan, 2007*.
10. US Patent 5914780, Digitisation of interferograms in Fourier transform spectroscopy.