Compact Fourier transform spectrometers using FR4 platform

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Abstract

A novel magnetic actuated polymer optical platform is integrated into lamellar grating and Michelson type Fourier transform spectrometers. 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 real-time measurement. The platform is capable of achieving ±250 μm DC deflection (i.e., 20 cm⁻¹ frequency resolution) in ambient pressure in the translational mode. A spectral resolution of 0.89 nm at 638 nm is demonstrated using this platform in a Michelson interferometer configuration. In addition, an overview of system integration methods including an optical position feedback mechanism is also discussed.

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1. Introduction

Infrared (IR) absorption spectroscopy is an established method for the detection and analysis of chemical and biological samples extensively used in a wide range of industrial and research oriented applications. Fourier transform infrared (FTIR) spectroscopy is one of the numerous IR spectroscopy techniques, distinguished by its unprecedented spectral discrimination paired with the inherent sensitivity. Due to its throughput and multiplex advantages, FTIR spectroscopy provides higher SNR and speed compared to conventional methods, such as grating or Fabry-Perot spectrometers [1]. Despite the major decrease in their size and increase in integrated software complexity in the last 30 years, most FTIR spectrometers are still large instruments consisting of individual opto-mechanical components, optics, sensors and processing electronics manually assembled in the traditional manner. Furthermore, the output of these spectrometers consists of spectra, which are interpreted either by individuals or by specifically developed algorithms, significantly reducing the throughput. Hence, Fourier transform infrared spectrometers are limited to be used when size and cost of the equipment are of secondary importance compared to performance.

IR spectrometers could potentially be used as 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 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 fermentation environment (CO₂), and countless other out-of-the-lab applications. Hence, a number of compact IR spectroscopy systems, mostly using MEMS technology, have been developed. Our group has demonstrated a vertical comb actuator based lamellar grating interferometer with a wide travel range in ambient, good optical efficiency, and compact structure [2]. The MEMS component utilizes vertical resonant comb drives for actuation, light dispersion, and optical path difference monitoring. Schenk has developed a moving grating spectrometer using a torsional microscanner [3]. A Michelson interferometer based FTIR spectrometer with a vertically moving resonant micromirror operating in vacuum was introduced by Kenda [4]. Manzardo has developed a novel MEMS lamellar grating based FTIR with 6 nm resolution in the visible region [5]. 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. Correira et al. developed a 16 channel CMOS integrated Fabry-Perot spectrometer which is highly miniaturized but has lower spectral resolution compared the other methods listed [6].

In this work, we present two compact FTIR systems in Michelson interferometer and lamellar grating configurations, 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 material has well engineered electrical, thermal and mechanical properties and the fabrication technology
is widely available at low-cost. There have been numerous attempts at integrating new functionality into PCB technology through novel usage of the FR4 substrate [7,8]. To our knowledge, our group was the first to utilize FR4 as an electro-mechanical platform with integrated optical and optoelectronic functionalities [9,10]. In this paper, we extend the use of this novel platform into FTIR spectroscopy. Measurements with narrow and broad band sources and with integrated position feedback are demonstrated.

In Section 2, the fundamentals of FR4 mechanics – material properties, fabrication, and actuation – are presented. A lamellar grating interferometer employing a FR4 platform and a new method of optical position feedback are discussed in Section 3. Section 4 presents a high performance Michelson type FTIR spectrometer with a FR4 platform bearing a retro-reflector. A discussion on the improvement of motion linearity and implementation of other spectroscopy methods with the presented platform are given in Section 5.

2. FR4 as a mechanical platform

2.1. Material properties and fabrication

Crystalline silicon is proven to be an excellent structural material for high performance microsystems due to its exceptional mechanical properties. However, crystalline silicon is very stiff and brittle; thus, low frequency (in the order a few hundred Hz) MEMS structures become very delicate and may not be able to survive the environmental shocks and vibrations. FR4, having a low Young modulus of about 20 MPA, is inherently a soft material and a good candidate for low frequency scanning applications, which usually are very challenging for silicon MEMS devices. Moreover, the electrical circuitry required to drive the FR4 mechanical elements can easily be integrated on the same circuit board with additional opto-electronic components, using conventional PCB manufacturing equipment. A drawback of FR4 based mechanics, as a result of conventional machining, is their relatively low structural precision compared to microfabricated components. The FR4 platforms presented in this paper have a minimum linewidth of 125 μm for the coil and a minimum mechanical feature size of 500 μm with a precision in the order of 100 μm. Using laser cutting techniques, precision of FR4 machining can be improved to about 20 μm, but this value is still far from sub-micron precision attainable with microfabrication techniques. The effect of low precision in the context of Fourier transform spectroscopy is discussed in the following sections.

Fig. 1 is a photograph of the conventionally machined FR4 scanner with a double-sided coil for electro-magnetic moving coil type actuation. In this actuation type, the coil on the platform has no function.

2.2. Electromagnetic actuation of FR4 scanners

FR4 platforms are actuated with electromagnetic forces, allowing both DC and AC operation. In the moving coil actuation configuration, a rectangular or circular permanent magnet is symmetrically placed underneath the platform, creating a magnetic field B. A current i passing through the device coil under this magnetic field induces a mechanical Lorentz force that vertically translates the platform \( F = B \times i \times l \). Fig. 2b is a schematic drawing illustrating this actuation principle. On either side of the platform, lateral component of the magnetic field and the direction of the coil current are in opposite directions, creating a net force on the
platform in the vertical direction utilizing all 4 sides of the coil. The vertical components of the field lines create lateral forces in opposite direction on either side of the platform that cancel each other. In the moving magnet configuration, a thin permanent magnet is attached on the platform, and an external electromagnetic coil is used for driving the system (Fig. 2c). Unlike the moving coil configuration, bi-directional actuation is possible, due to the attraction and repulsion forces between the permanent and electrical magnets. Due to the large dimensions of the platforms, a significant amount of electromagnetic force can be generated with both type of actuation, 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 torsional or translational modes, also making the device useful for various 1D and 2D beam scanning applications.

Measured frequency response for the out-of-plane (z) translation mode of the platform with moving coil actuation is shown in Fig. 3a. The experiment was performed with a permanent magnet creating 0.1 Tesla average magnetic flux density on the coil and a drive current of 10 mA. The system behaves like an ordinary 2nd order system with a resonance frequency of 499 Hz and resonance deflection of 85 μm. Slight asymmetry in the resonance curve is due to the spring stiffening effect. In moving magnet actuation configuration, the resonance behavior is similar, but the resonance frequency is significantly lower due to the additional mass of the attached magnet, and the maximum achievable deflection is higher due to stronger EM force (Fig. 3b). Effect of spring stiffening is much more evident in the moving magnet actuation case, due to much higher achievable deflection. As can be seen in Fig. 4, the amount of translation increases linearly at low drive currents, and its rate slowly drops due to spring stiffening effect at higher drive amplitudes.

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 also be used as a rotating grating spectrometer similar to the MEMS spectrometer in [3] with higher spectral resolution and lower electronics bandwidth requirements but still provide spectrum in a fraction of a second [11].

3. Lamellar grating interferometer with FR4 platform

Fourier transform spectroscopy (FTS) is an established method to analyze spectral content of a radiation source using an interferometer. In a Fourier transform spectrometer, the radiation from the source entering the interferometer is divided into two mutually coherent beams, either by a beamsplitter (amplitude division) or diffraction grating (wavefront division). Two beams experience different optical paths before they are superimposed to yield an interferogram, which is defined as the interference intensity as a function of the optical path difference. Lord Rayleigh discovered that the interferogram is actually a sum of cosine waves for all the wavelength components in the polychromatic source, multiplied, in each case, by a factor reflecting their intensity. Hence, the interferogram can mathematically be represented as the cosine transform, or the real part of a Fourier transform of the source spectrum. In order to be able record a time-resolved interferogram, Fourier transform spectrometers employ translating, or rotating mirror elements to scan the optical path difference between the interferometer arms. This section describes a wavefront division FTS (also called a lamellar grating interferometer-LGI [12]) implemented with the aforementioned FR4 platform.

The basic operation principle of LGI is shown in Fig. 5. Radiation from the source to be measured is separated into two coherent wavefronts through reflection from a variable-depth binary diffraction grating, and these wavefront interfere via diffraction as they propagate. Beyond Fraunhofer distance, the two wavefront are fully interfered to form a discrete diffraction profile with several orders separated by a constant angle determined by the wavelength of the radiation and the grating period. An interferogram can be obtained by the recording the 0th order intensity recorded as a function of the distance between the front and the back facets of the variable depth-diffraction grating, μ. Please note that, an LGI, contrary to a...
grating spectrometer, do not operate at the 1st diffraction order, and
the free spectral range of the system does not depend on the diffrac-
tion angle.

If a linearly polarized plane parallel radiation with wavenumber 
\( \sigma \), and wavelength \( \lambda \), is incident normally upon a binary diffraction
grating as shown in Fig. 5, the far-field radiation intensity in the 0th
diffraction order is given as [2]:

\[
I(d) = B \cos^2(2\pi \sigma d) = \frac{B}{2} (1 + \cos(4\pi \sigma d))
\]  

(1)

where \( d \) is the grating depth, and \( B \) is a scaling factor depending
on the illumination, reflectivity of the grating, and the grating fill-
factor. The AC component of the 0th order diffraction intensity as
a function of grating depth \( d \), which is simply a cosine modulation
with period \( \lambda/2 \) for a monochromatic source, is called the inter-
ferogram. For a broadband source with continuous power spectral
density and a grating scan range of \( \pm d_{\text{max}} \), the interferogram \( F(d) \)
becomes

\[
F(d) = \int_{-\infty}^{\infty} B(\sigma) \cos(4\pi \sigma d) \, d\sigma \, \text{rect} \left( \frac{d}{d_{\text{max}}} \right) 
\]  

(2)

where \text{rect} is the boxcar function (equals to one between \(-d_{\text{max}}\)
and \( +d_{\text{max}} \), and zero otherwise) truncating the interferogram due
to the finite travel range of the grating. The spectral resolution
of FTS systems are limited by the width of the Fourier transform
of this rect function, which is also called the instrumental or the
line-shape function of the spectrometer. Eq. (2) shows that there
exists a Fourier relationship between the interferogram, and the
power spectral density (spectrum) of the measured source. Different
FTS configurations are distinguished by the method they use to
obtain the interferogram; however, the processing of the interfer-
ogram is common among all variants. The advantages of LGI, such
as the simple operation principle and lack of complex optics enable
the construction of very compact spectrometer. A fully functional
spectrometer system can be constructed using a binary diffraction
grating, a single photodetector and electronics for processing the
detector output.

Fig. 6 is a schematic drawing of the LGI based Fourier transform
spectrometer employing an FR4 platform as the movable compo-
nent. An aluminum coated silicon grating is placed on top of the FR4
platform to form the static fingers of the movable grating required
for the LGI system. The 30 \( \mu \)m thick micromachined silicon grating
has a period of 140 \( \mu \)m and 50% duty cycle (the finger width and the
gap between the fingers are both 70 \( \mu \)m). A secondary grat-
ing is placed underneath the FR4 platform for an optical position
feedback system that will be discussed in the next sub-section.

Although the spectrometers developed in this work target the IR
region, experiments were performed using visible sources, instead
of an IR source. Since the operation principle of FTS is independent
of the wavelength, using a visible source significantly facilitated
the experiments, while allowing the effective evaluation of the sys-
tem performance. Fig. 7 presents the experimental laser reference
and interferogram data obtained with the LGI setup. For reference
interferogram, a blue-violet laser diode (408 nm) was used, and
the measured source is a red laser diode. Maximum travel range
of the FR4 movable platform is limited to 22 \( \mu \)m, yielding a spectral
resolution of 500 cm\(^{-1}\). The effect of low precision of the FR4 plat-
form is the main limiting factor on maximum travel range, since
beyond 22 \( \mu \)m, interferogram and laser reference signal becomes
significantly deteriorated due to mirror wobbling.

There are two fundamental problems with the presented LGI
system. The net OPD for light reflected from the mirror and the
grating is always positive due to the finite thickness of the grat-
ing structure (minimum OPD is 30 \( \mu \)m for the presented system).
The effect of this is equivalent to high-pass-filtering of the spec-
trum, where the cutoff frequency is determined by the lowest value
of the OPD. Hence, the slowly varying portion of the spectrum is
omitted, but the sharp spectral lines remain intact. Therefore, it
is ideal for detecting narrow spectral lines if the deflection range
can be increased. The second problem associated with this method
is related to the fabrication tolerance. The moving grating is the
heart of the 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 \( \lambda \) 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 amount, particularly for large deflections, resulting in signif-
cant distortion the acquired interferograms. A redesign that can
provide larger linear displacements is required. A more complex
system with multiple actuation coils with position feedback from at
least 3 positions on the surface would improve the linear deflection
range.

3.1. Optical position feedback and interferogram sampling

Accurate real-time sampling of the interference versus OPD is a
crucial requirement for interference-based spectrometers. Hence,
an optical position feedback mechanism for the FR4 platform
is implemented. Position feedback and sampling clock signal is
obtained using the backside of the FR4 platform and the fixed grat-
ing referred to as the feedback grating. A visible laser diode (LD)
at \( \lambda_{\text{ref}} \) can be used to generate a non-linear sampling clock sig-

Fig. 6. Schematic drawing of the lamellar grating interferometer employing a FR4
platform.
the laser reference signal from the feedback grating produces spatially uniform samples due to the precise $\lambda_{\text{ref}}/4$ displacement of the platform between each zero crossing. A very similar method is commonly used for conventional FTIR systems, but the feedback interferometers are almost always of Michelson type.

The common practice to utilize the laser interferogram is to produce a sampling clock signal from the laser interferogram with a zero-crossing detector; however, electronic processing delays can lead to sampling time errors that manifest themselves as spectral noise [4]. An elegant interferogram sampling method was developed by Turner et al. [13] in order to overcome the sampling delay issue in Fourier spectrometers and adapted in this work. In this system, both the laser fringe and the interferogram are sampled with separate analog-digital converters (ADCs) synchronized by a single high frequency clock signal (Fig. 8). The zero-crossing times of the laser fringes are computed with a linear interpolation step, followed by a cubic interpolation of the interferogram to compute its value at the new found zero-crossing time (Fig. 9). This method requires a faster ADC than using the output of a zero-crossing detector as a sampling clock for the ADC, but the sampling time errors that may arise due to electronic delays can be eliminated completely.

4. Michelson interferometer with FR4 platform

Most of the FTS systems in use today are in amplitude division form, based on a Michelson, Mach-Zender or another type of interferometer with a moving mirror. In this configuration, the light beam from the measured source is amplitude split by a beam splitter and both arms reflected from two flat mirrors—one static, one movable. Then these arms are superimposed and an interferogram,
which is mathematically identical to 0th order interferogram of an LGI, can be recorded as a function of the mirror displacement. The optical path difference between two arms of the interferometer can be set to zero; therefore, the entire interferogram can be recorded, unlike the FR4 based LGI. A major disadvantage of this method compared to the LGI configuration is requirement of the additional optical components (beam splitter, focusing optics) and tighter alignment tolerances.

We have recently presented a FR4 based Michelson type FTS with retro-reflectors (corner cubes) [13]. A small and light-weight plastic corner cube with 50 nm evaporated aluminum layer was made and attached on top of the FR4 platform. Retro-reflectors are an effective solution to correct for the wobbling problem, which are also widely used in bulk FTIR spectrometers to correct for mirror misalignments. Integration of retro-reflectors drastically improved the maximum allowable travel range of the FR4 scanners at a cost of lower acceptance angle, due to their small aperture size. A schematic drawing and a photograph of the built spectrometer are shown in Fig. 10a and b, respectively.

**Fig. 11** plots experimental laser reference and interferogram signals acquired with the setup together with the associated computed spectrum. Maximum travel range of the platform is extended to 500 μm (±250) without distorting the interferogram, and theoretical spectral resolution is improved to reach 20 cm⁻¹. A triangular apodization function was applied on the interferogram to suppress the side lobes of the spectral peak which result from the rectangular instrumental function of the spectrometer. **Fig. 11c** shows that the spectral resolution of the spectrometer is 0.89 nm at 638 nm, slightly worse than the theoretical resolution of 0.8 nm at this wavelength, and outperforming the commercial grating spectrometer (Ocean Optics USB2000) used to record the reference measurement. The 2% wavelength accuracy is slightly worse than the LGI data, and it is predicted to be due to the thermal drift of the reference laser wavelength. This minor problem can be solved by temperature stabilization of the reference laser diode with a thermo-electric cooler.

Due to the poor surface uniformity of the plastic retro-reflectors used in the experiments, white light interferogram acquisition presented a significant challenge. Hence, the retro-reflectors were replaced again with flat aluminum coated silicon mirrors, and the travel range kept at ±20 μm to minimize interferogram distortion. The recorded interferogram for a red LED and the associated spectrum acquired with these settings are given in **Fig. 12**. The comparison of the measured spectrum with the reference spectrum shows that, even though the center frequency was correctly decoded by the spectrometer, the measured linewidth is almost twice the actual value (35 nm measured versus 20 nm actual FWHM linewidth). This discrepancy is not due to the low maximum deflection, since the theoretical resolution with ±20 μm is 8 nm at 638 nm. Furthermore, the shape of the interferogram clearly shows that at the extremes of the interferogram, interferometric modulation disappears due to the low coherence length of the source. Hence, it can be claimed that the reason behind the broadening of the measured spectra is the distortion of the interferogram due to the discrepancy in mirror motion. Dynamic surface profile measurements for the mirror are necessary to fully explain this effect.

5. Discussion

The presented FR4 platform based spectrometer systems has several advantages over existing portable MEMS based, or bulky FTIR spectrometers. The large clear aperture, long mirror travel range and possibility of conventional machining are clear advantages over the existing MEMS based spectrometers. On the other hand, compared to the bulky FTIR systems, they are still more compact and portable, faster, and easier to build. However, the major drawback of this approach, as shown in this work, is the limited motion precision, which is severe limitation, especially for the lamellar grating interferometer system. Hence, the extension of the linear translation range of the platforms is essential to improve the. 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 still becomes a problem for the current design. The linear motion range can be extended using multi-point actuation and associated position feedback and close loop-control. Fabrication of multiple coils on the same platform introduces no fundamental fabrication challenge, and the grating based position feedback system presented in this system, or the back-emf sensor coils are compact enough to be easily integrated with the system. This close-loop operation approach will be pursued as future work.
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Fig. 11. (a) Experimental interferogram and laser reference data acquired using the FR4 Michelson interferometer setup. Peak-to-peak mirror displacement is 500 μm (off-resonance sinusoidal moving magnet actuation at 10 Hz). (b) Output of the FR4 spectrometer with 0.89 nm resolution and a commercial spectrometer with 2 nm resolution.

Fig. 12. (a) Interferogram recorded with a red LED source. (b) Associated measured spectrum compared with a reference measurement.

5.1. Conclusion and future work

Two compact Fourier transform spectrometer systems in Michelson interferometer and lamellar grating interferometer are demonstrated using a vertically translating FR4 platform. An experimental spectral resolution of 0.89 nm is demonstrated using a red laser diode with the Michelson interferometer. Real-time operation, long and controllable travel range, simple 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

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