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Miniaturized Fourier transform spectrometer for gas detection in the MIR region

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ABSTRACT

Selective multi-gas detection is often based on spectroscopic methods in the infrared region. The resulting setup consists of a spectrometer and the probing setup where often the spectrometer makes the sensing device large and heavy and does not allow easy on the field integration. We report on the application of a silicon micromachined lamellar grating interferometer in a Fourier transform infrared spectrometer for the detection of gases in the mid infrared region. The spectrometer heart was miniaturized consequently to fit in a box of 30 mm × 30 mm × 55 mm. The Fourier transform infrared spectrometer was equipped with mid infrared optical fibers for light coupling. Gas measurements in the mid infrared region were focused on specific gases (CO_2 and CH_4) in order to determine the limit of detection and the selectivity that could be obtained using such a micro-spectrometer. Using two different spectral regions we were able to detect concentrations of carbon dioxide over a span from 100 to 9000 ppm with a theoretical detection limit evaluated less than 10 ppm. The performed gas measurements showed the proof of principle of a miniaturized Fourier transform infrared gas analyzer based on a micromachined spectrometer and fiber optics.

1. Introduction

The current Fourier transform infrared (FTIR) systems are bulky, expensive and need well-controlled operation conditions. Therefore their use is often limited to laboratories. There are systems available to be installed on the field but due to their large size and the stabilization of operation conditions they become expensive. The developments of a micro FTIR gas analyzer, having a smaller size and at a lower cost would enlarge the fields of application. Most compact spectrometers use the dispersive effect of a grating. Miniaturization is only possible to a certain extend and often leads to tremendous performance losses.

Most of the systems in the field are Fourier transform spectrometer (FTS) systems. If such a system is miniaturized several parameters will be affected and the system characteristics are altered heavily [1–4]. Small footprint of the device will only allow small active areas and therefore lower throughput. If the system is fiber coupled, one has to take into account that fiber delivery usually causes coupling losses when the measurement infrastructure is not optimized for such conditions. The small volume of the devices limits the possible for light and illumination management. The concept presented here is a novel MEMS-based Fourier spectrometer operating as a lamellar grating interferometer and realized on silicon [5]. Lamellar grating systems are known for other wavelengths regions [6,7] but were not implemented in the MIR because of technological difficulties. We have demonstrated before its application for gas detection in the near infrared region [8]. Here we report on the adaptation and the use of the spectrometric module for gas measurements in the MIR region.

2. Features of the micromachined spectrometer

2.1. Operational principle of lamellar interferometer

A lamellar grating spectrometer has the specificity that it is a common path interferometer and the wave front is split spatially and not in intensity by a beam splitter as in conventional Michelson systems. It usually setup in reflection as shown for the far infrared [9–11] and other millimeter wave regions [12]. Lamellar grating systems give the possibility to realize very compact interferometer modules if the driving mechanism can be miniaturized too. One demand is to keep the size of the active area of the lamellar grating as large as possible and realize a small period in order to have large separation angles of the diffracted beams. This became possible with micromachining techniques. For the MIR region a good compromise is a period of 100–300 μm which is convenient for near infrared and mid infrared interferometer systems [13,14].

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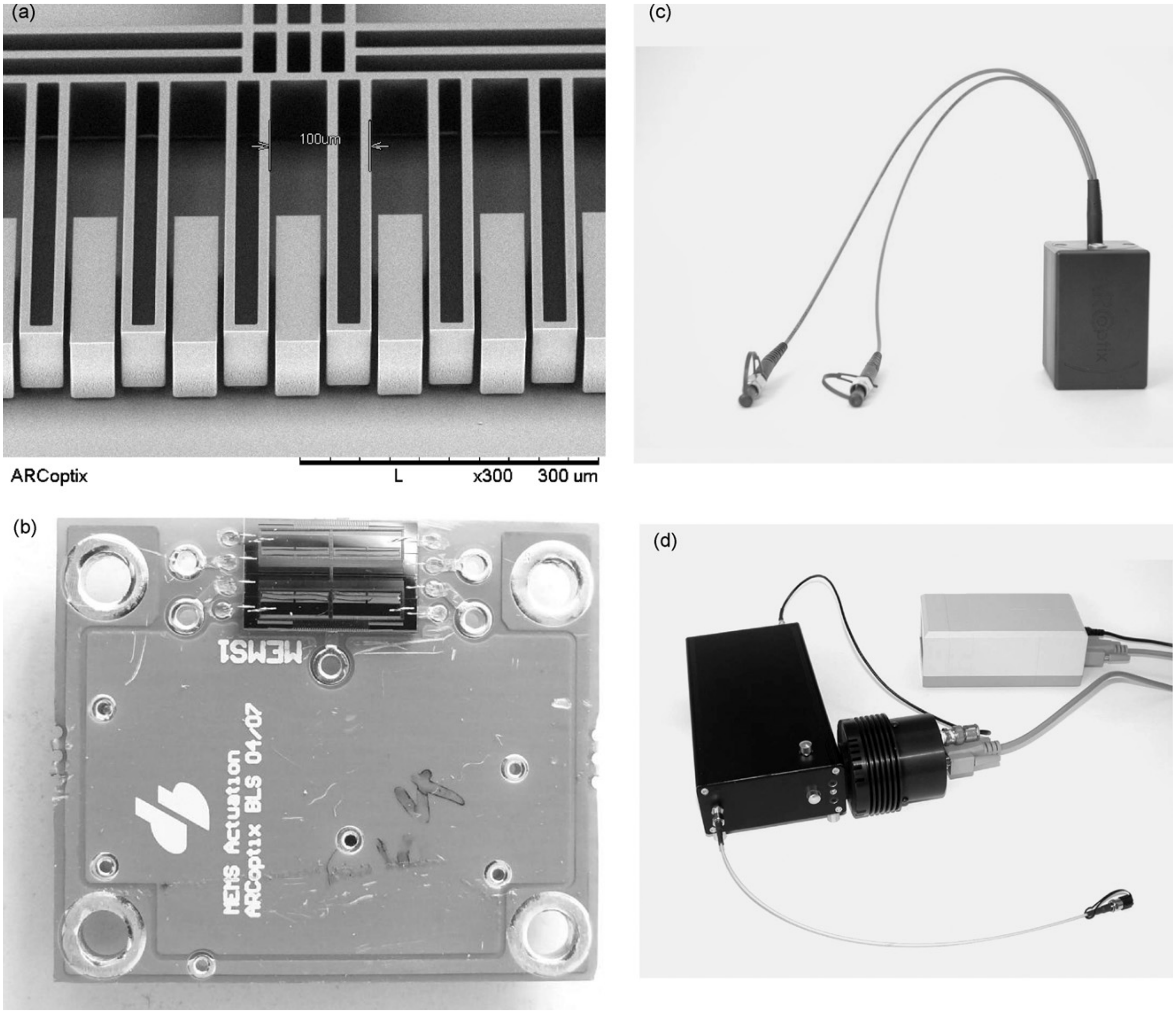

Fig. 1. The building principle of the micro FTIR module. A MEMS chip shown in (a) is used as the core of the interferometer, mounted on a PCB as shown in (b) and hermetically packaged in housing comprising optical components for illumination management in (c). A detector and electronics are embodied to complete the spectrometer in (d).

Smaller periods below 50 μm might be adapted for particular applications at shorter wavelengths [15,16]. An additional aspect is the driving of the grating that can be realized as a direct electromagnetically driven actuator known from Micro-Electromechanical Systems (MEMS) or in a hybrid way. Non-conventional electrostatic scanning mechanisms of MEMS scanner often suffer from a limited movement range. For MEMS, a typical optical path that can be obtained today is smaller than 1 mm. Since that systems are often operated in resonance to gain stability the control of scan speed is not possible but the stability is very high and allow even operation without laser reference. One problem of electromagnetically driven systems is the scan speed. At a typical frequency of several hundred Hz one needs data transmission rates of more than 1 GHz to assure a reasonable number of points within a single measurement.

2.2. Fast scanning MEMS spectrometer characteristics

The heart of the lamellar MEMS-based FTS used in our experiments is a silicon chip of 5 mm × 3 mm size. It contains a lamellar grating arrangement as seen in Fig. 1a with a period of 100 μm and comb drive actuators. This MEMS scanner with an active area of 75 μm × 3000 μm is bonded on a PCB as seen in Fig. 1b. The size of the PCB is given by the incorporated driving electronics and leads to a PCB of 25 mm × 20 mm × 4 mm. Mirror optics is used to focus the light from the entrance onto the MEMS active area and couple the modulated light back into the output. This optics needs a certain travel distance of light to optimize coupling. Light is injected via fluorinated fibers from IRphotonics. The fiber diameter is 100 μm. MEMS chip and optics components are incorporated in a hermetically sealed interferometer module of 55 mm × 30 mm × 30 mm shown in Fig. 1c. The common path design allows to use only one optical element for collection and focusing of light. The MEMS scanner operates at 200 Hz and allows up to 300 μm path difference corresponding to approximately 20 cm^{-1} resolution. A detector, the electronics for driving and data acquisition are integrated into a slim aluminum housing as seen in Fig. 1d. The resonance operation is typical for MEMS movement as it assures a reliability of the scanning mechanism that is otherwise only found in laser controlled interferometers. Typical resonance frequencies are above 200 Hz and usually 3000 measurements points are recorded which leads to measurement times of 2 μs per point. A high-speed detector has to be used. At high speed the instrument noise will be given by the detector and it amplification electronics. We used a mercury–cadmium–telluride (MCT) detector from VIGO systems with sensitivity between wavelengths of 2 and 5 μm. The detector is thermoelectrically cooled down to −70 °C. Due to the