An integrated optical method to readout µ-Coriolis mass flow sensors

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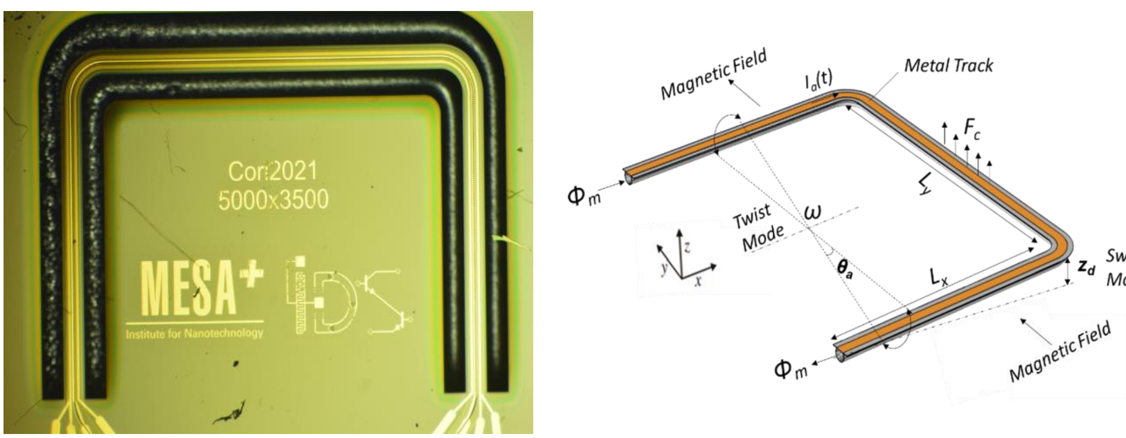
ABSTRACT

This paper presents a novel readout for a µ-Coriolis mass flow sensor based on a differential optical reflective method, using a vertical-cavity surface-emitting laser (VCSEL) and two photodiodes (PD). The new readout detects change in applied mass flow rate by measuring the phase shift between the two photodiode signals. Such a setup offers a non-contact and robust sensing method. Measurements are presented for mass flow of DI-water up to 10 gram/hour resulting in a phase shift of 8.7 degrees.

Keywords: VCSEL, PD, µ-Coriolis mass flow sensor, MEMS, microfluidics, differential optical readout

1. INTRODUCTION

MEMS based microfluidic devices such as a µ-Coriolis mass flow sensor offer multiparameter sensing and miniaturization in the microfluidic domain to detect several fluid properties such as mass flow, density, pressure and relative permittivity [1][2]. The device used in this paper consists of a thin, freely suspended U-shaped tube (microchannel) with a width of 200 µm, depth of 70 µm and 2.5 µm wall thickness (1.4 µm silicon-rich silicon nitride inner layer and 1.1 µm tetraethoxysilane outer layer) that has dimensions of 5 mm x 3.5 mm as shown in Figure 1a. The tube is fabricated using MEMS based surface channel technology (SCT) [3]. Such devices are used to measure fluid flow down to a few g/h [2][4], typically with a capacitive readout. However, the capacitive comb structures are sensitive to shocks and water hammering effects, which cause the structures to entangle with each other, leading to permanent damage of the device [5][6].



(a) (b)

Figure 1. a) Photograph of the U-shaped µ-Coriolis mass flow sensor used in this paper, b) Working principle of the µ-Coriolis mass flow sensor actuated using Lorentz forces.

In this paper we demonstrate the potential for an optical readout method to detect the change in mass flow rate by measuring the phase difference between the reflected light intensities using a chip based vertical-cavity surface-emitting laser (VCSEL) source and two photodiodes (PDs). Such a method can prevent damaging the tube due to the water hammering effects during measurements and act as a robust, non-contact sensing technique.

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2. MEASUREMENT PRINCIPLE

The measurement principle of the µ-Coriolis mass flow sensor is shown in Figure 1b. The tube is actuated using Lorentz forces by an external magnetic field and the current applied, $i_a(t)$, on the metal track. The actuated tube will experience a twist mode vibration around the x-axis indicated by ω (angular velocity) at its resonance frequency and will have an angle of tilt, θ_a. When there is a fluid flow Φ_m (mass flow) inside the tube, the Coriolis forces F_c will result in an out-of-plane movement z_d in the swing mode. This movement is proportional to the mass flow and the angular velocity of the tube as described in the following equation:

$$\vec{F_c} \approx -2L_y\left(\vec{\omega} \times \vec{\Phi}_m\right) \tag{1}$$

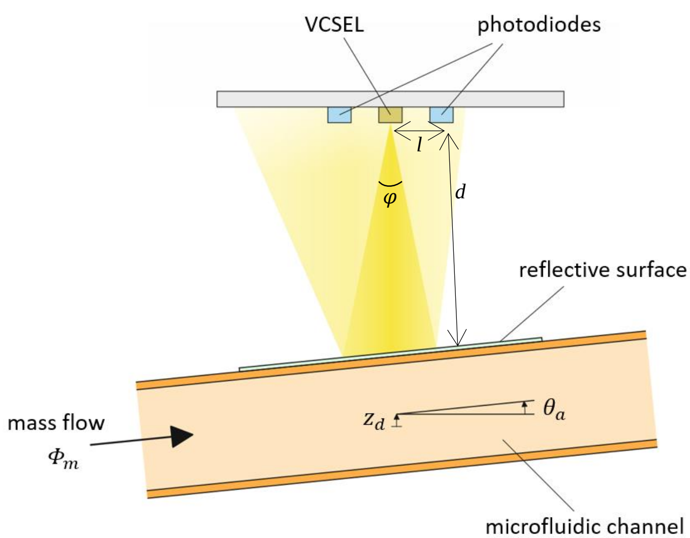


Figure 2. Basic measurement principle of the optical readout.

The basic measurement principle for this work is illustrated in Figure 2. We use a chip based VCSEL light source and two PDs to detect the twist and swing mode vibrations. The metal tracks on the tube act as a reflective surface. The emitted light from a VCSEL with divergence angle φ is reflected on the channel of the µ-Coriolis mass flow sensor. Photodiodes are placed at each side of the VCSEL to receive the reflected light. A tilt θ_a of the flow channel due to the actuation of the sensor should result in differential change in received light. An out-of-plane motion z_d of the flow channel due to a mass flow Φ_m should result in common variation in received light. The total change in reflected light intensities due the tilt θ_a and out of plane motion z_d will result in a phase difference between the two photodiodes. This phase difference is proportional to the mass flow rate [5]. The reflected light intensity signals received at the center of the right photodiode IR and left photodiode IL follow the equation from [7] and [8]:

$$IR = \frac{2*P*\cos 2\theta_a}{\left(\pi*\left(d+z_d+l\sin 2\theta_a+(d+z_d)\cos 2\theta_a\right)*\tan\frac{\varphi}{2}\right)^2} * \exp\left[-\frac{2*\left(l\cos 2\theta_a-(d+z_d)\sin 2\theta_a\right)^2}{\left(\left(d+z_d+l\sin 2\theta_a+(d+z_d)\cos 2\theta_a\right)*\tan\frac{\varphi}{2}\right)^2}\right] \tag{2}$$

$$IL = \frac{2*P*\cos 2\theta_a}{\left(\pi*\left(d+z_d-l\sin 2\theta_a+(d+z_d)\cos 2\theta_a\right)*\tan\frac{\varphi}{2}\right)^2} * \exp\left[-\frac{2*\left(-l\cos 2\theta_a-(d+z_d)\sin 2\theta_a\right)^2}{\left(\left(d+z_d-l\sin 2\theta_a+(d+z_d)\cos 2\theta_a\right)*\tan\frac{\varphi}{2}\right)^2}\right] \tag{3}$$

where, l is the distance between the VCSEL and each photodiode, P is the emitted power of VCSEL source, and d is the distance between the VCSEL and the reflective surface. A change in mass flow rate will result in a change in phase difference between the amplitudes of the received light intensities at the photodiodes as described above.

3. DESIGN AND REALIZATION

Figure 3a, describes the design and structure of the µ-Coriolis mass flow sensor with integrated optical readout system. The VCSEL (which has a center wavelength of 850 nm and a beam divergence φ of 20º) and the photodiodes were bonded with thermal epoxy and assembled on a glass substrate as shown in Figure 3b. The distance between the VCSEL and each of the photodiodes l was set to 400 µm. The distance between the reflective surface on the microchannel tube and the optical components d was chosen to be 1.6 mm to receive optimum change in power due to reflected intensities as obtained from Eq. 2 and Eq. 3.

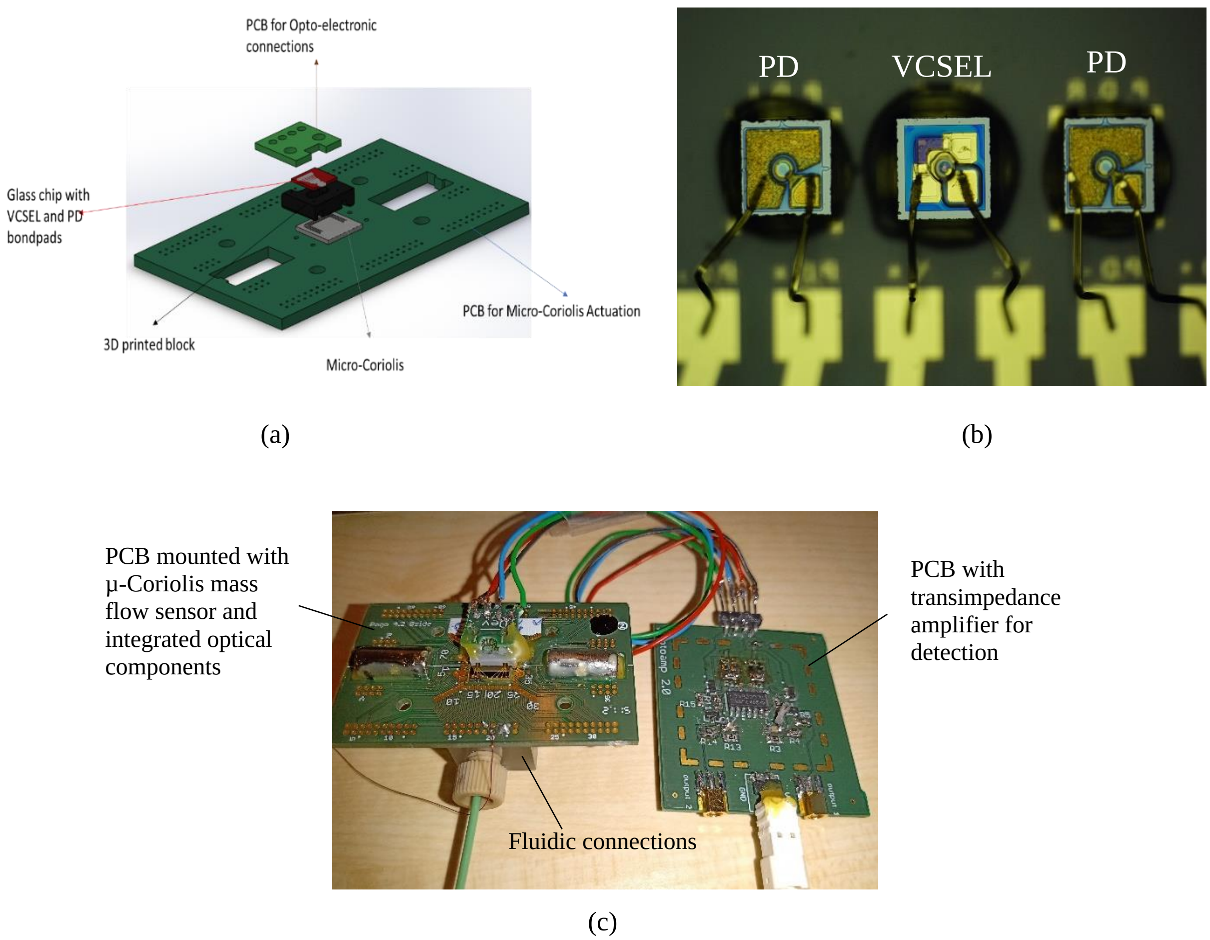
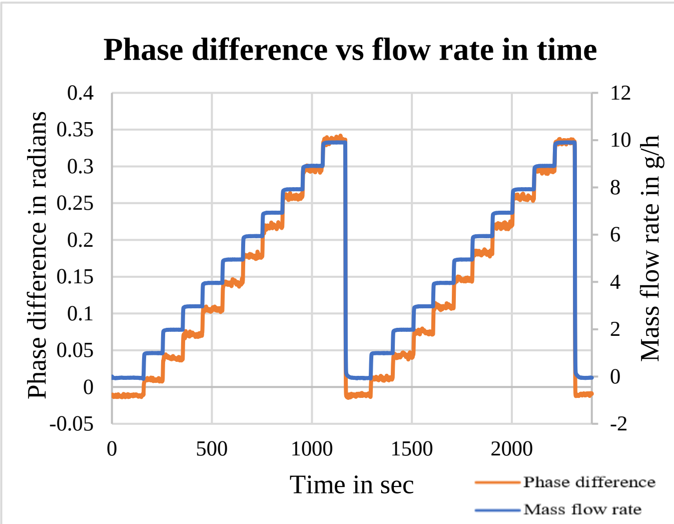


Figure 3. a) Design of the µ-Coriolis mass flow sensor with optical readout, b) Photograph of the VCSEL and photodiodes assembled on a glass substrate with an equal distance of 400 µm between them, c) Photograph of the final assembly of the optical readout with fluidic and electronic connections.

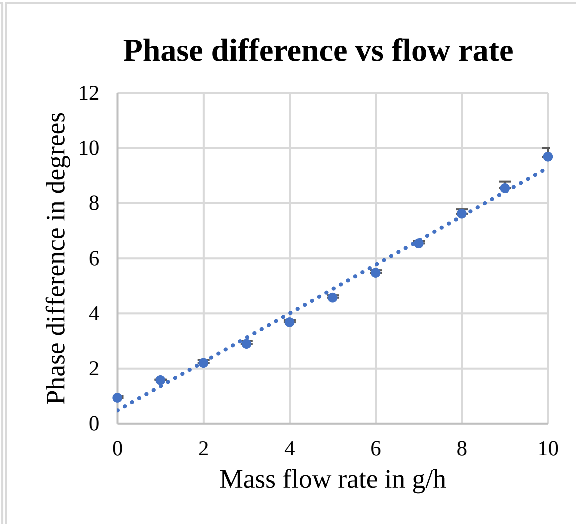
Active alignment of the optical components to the µ-Coriolis mass flow sensor, Figure 1a, used in this paper was done manually at zero flow. A 3D printed spacer was used to separate the glass chip bonded with VCSEL and PD, and the mass flow sensor. A PCB containing a transimpedance amplifier was designed for this application. The final assembly with magnets mounted for Lorentz force actuation, and electronic and fluidic connections is shown in Figure 3c, resulting in a compact optical readout for the µ-Coriolis mass flow sensor.

4. RESULTS AND DISCUSSION

Measurements were performed using flow of DI water. The mass flow was controlled from 0 to 10 gram/hour in steps of 1 gram/hour. Two lock-in-amplifiers were used to read out the change in phase between the two photodiode signals. Lab View (NI DAQ) was used to record and plot the phase difference in radians and the applied flow rate as a function of the time as shown in Figure 4a. The phase difference was converted to degrees and is plotted as a function of mass flow, see Figure 4b, in the flow range of 0 to 10 g/h.



(a)



(b)

Figure 4. a) Measured phase difference and applied mass flow rate as a function of time, b) Phase difference plotted as a function of mass flow. The applied mass flow was increased from 0 to 10 g/h in steps of 1 g/h.

In theory, change in phase difference between the reflected intensities of the two photodiodes should be proportional and linear to the change in mass flow rate. However, there are some practical limitations that should be considered during the measurements with the optical readout. At zero flow, the results show an offset. This may be due to non-perfect alignment of the glass substrate with VCSEL and PD to the µ-Coriolis mass flow sensor. An existing µ-Coriolis mass flow sensor was used for this work. The design had a small width of the reflective surface. This had an influence on the reflected light received at the photodiodes. How this might affect the performance aspects like stability and linearity of the sensor needs to be further investigated. A dedicated µ-Coriolis sensor design with larger reflective surface might improve the stability as well as make the alignment of the optical components to the microfluidic sensor less challenging.

5. CONCLUSION AND OUTLOOK

In this work, we designed, realized and tested an optical readout for a µ-Coriolis mass flow sensor using the VCSEL and the two PDs as a proof of concept and presented the preliminary results. We showed that the phase difference between the two photodiode signals is proportional to the mass flow, with a change in phase of 8.7 degrees at 10 gram/hour using flow of DI water. In the current design we used an existing µ-Coriolis mass flow sensor. Future research will include the design and fabrication of a dedicated microfluidic chip with a larger reflective surface in order to improve both sensitivity and stability of the device.

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