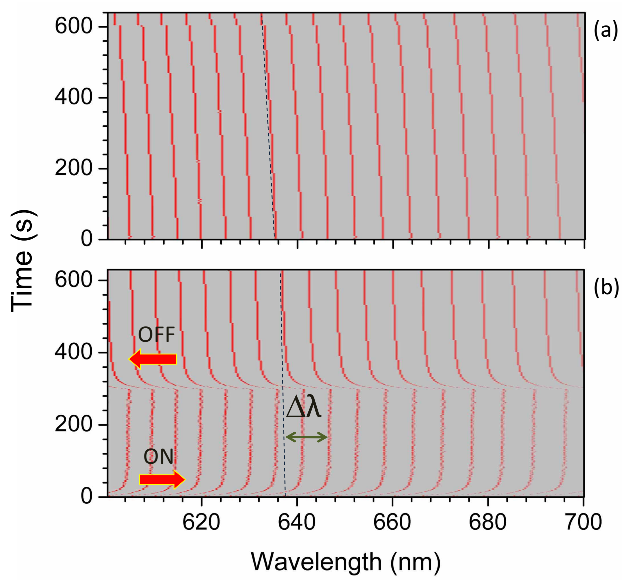

Fig. 4. Spectral shifts of the FP-fringes over time by switching ON/OFF peristaltic pump. The pump rotation speeds are: (a) 0.1 and (b) 10 rpm; corresponding to: 0.38 cm/s and 0.38 m/s flow velocity. The pump switching ON-OFF transients are marked; dashed-lines are eye guides for the peak tracking. Spectral sampling rate: point per 1 s (a) and 5 points per 1 s (b).

switching performance of the FP-cavity and summarizes monitoring of spectral shifts of the FP fringes at different flow rates and the on-off switching transients. Narrowing of the FP cavity (due to a PMMA swelling) at the lowest flow rate was changed to an expansion at the larger speeds. Even at the highest flow rates of $v \simeq 1$ m/s the adhesive was holding the plates well and after the pump was switched off, the FP fringes followed the standard slow flow behavior (see, extended regions in Figs. 4(a) and 4(b)). The on-off switching at the highest flow rates of $v \simeq 1$ m/s (limited by a tube's detachment from the channel) was achieved without degradation of the FP cavity nor channel. Adhesion of a TA film to the top and bottom plates remain uncompromised (without recognizable leaks and delamination) after up to 6 hours of testing. During one hour stress-testing of a structural integrity of a microfluidic channel water is pumped at the maximum speed ($v \simeq 1$ m/s) and pump makes ~ 24000 "On" and "Off" cycles (similar testing is shown in Fig. 4). The only reason of channel degradation was swelling of the top PMMA plate as we reported earlier and for the water solutions occurred after prolonged several hours of operation [10]. These optofluidic chips are intended for the fast measurements which are shorter than 5-10 min.

The pressure changes in the channel can be measured by monitoring spectral shifts of the FP cavity (see, Fig. 4). To quantify the pressure change, ΔP, we, first, measured the vertical height of a spraying solution from a nozzle and, then, velocity is calculated from the balance of kinetic and potential energies. At the fixed flow rate, the velocity of solution in the tube of arbitrary diameter is calculated from Bernoulli equation (the diameter of the syringe tube used as nozzle is known):

$$P_1 + \rho g h_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g h_2 + \frac{1}{2}\rho v_2^2 \quad (1)$$

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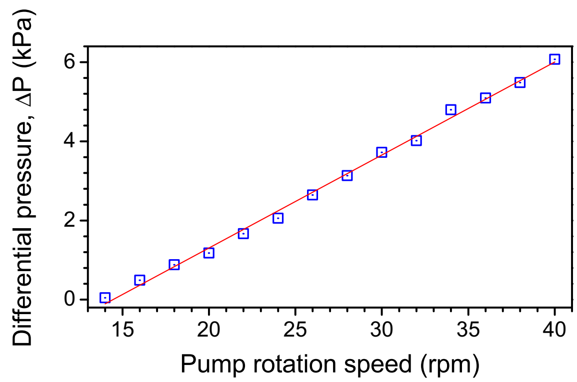

Fig. 5. Experimental measurements of a differential pressure, ΔP, created by the peristaltic pump at different pump rotation speeds. Line is the linear fit.

where P_1 and P_2 are pressures in the pump and in atmosphere (101325 Pa), respectively; ρ is the density of water, $g = 9.8$ m/s^2 is the Earth's gravity constant, h_1, h_2 equals zero as both nozzle and pump are at the same ground level, v_1 is the speed of liquid in the pump, whereas v_2 is the speed of liquid exiting the nozzle.

Figure 5 shows results of the differential pressure, ΔP, calculations vs rotation speed of the peristaltic pump. At the pumping speed of 10 rpm, the pressure estimate was $\Delta P \sim 160$ Pa. The shift of peak position in experimentally observed spectrum ($\Delta\lambda$) was $\sim$12 nm (at the wavelengths around $\sim$785 nm). This defines a sensitivity of device $\Delta\lambda/\Delta P \simeq 0.075$ nm/Pa. As the spectral resolution of our portable spectrometer is only 0.4 nm, we can reliably detect change of $\Delta P \simeq 5.33$ Pa in the channel.

The spectral shifts of FP fringes can be used as a flow meter over the dynamic range of 100 as shown in Fig. 4. The flow velocity, v, of liquid whose viscosity is, μ, driven by the pressure difference, ΔP, scales with the transverse dimensions of channel, b, and its length, L as [21]: $v \propto \frac{b^2}{\mu L}\Delta P$.

The FP cavity build in a microfluidic channel is acting as a pressure or flow velocity sensor. Shift of the fringes over approximately the free spectral range $\Delta\lambda \simeq 10$ nm corresponds to the FP cavity change by $\sim \lambda/2 \simeq 325$ nm, i.e., an increase by 1.3% as was observed in the case of 0.14 m/s.

4. Discussion

The peak positions of FP fringes undergo small erratic shifts as flow rate increases (see, Fig. 4(b)). It is related to the pump's noise whose rotation speed is known (e.g., 10 rpm for 0.38 m/s flow velocity). Fourier analysis (not shown) revealed that spectral shifts of FP fringes are related to the rotation speed of the pump and is the main source of the noise in spectral measurements. Syringe pumps would be preferable for measurements at increased signal-to-noise ratio.

Data analysis of Figs. 3 and 4 shows that changing of refractive index or flow rate in the channel can be monitored by spectral shifts of the FP fringe pattern. The presence of a slow PMMA swelling in water can be easily accounted for as a baseline shift (it can be slightly different from channel to channel). This shows that 10 ml per 5 min at a 1 m/s flow velocity is a feasible target for filtration in a simple channel held together by an adhesive spacer, which

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defines the channel geometry.

The presented simple channels can be operated at flow rates corresponding to the Reynolds number (Re) $Re \equiv \frac{\rho v x}{\mu} > 2300$, where v is the velocity of flow and x is the characteristic linear dimension of the flow. The Reynolds number represents the ratio of the inertia to viscous force and predicts onset of turbulency of a 3D flow when $Re > 2300$. The optofluidic channels can be used for a little explored turbulence onset phenomena in 2D flows in an easy and accessible way, e.g., using selector of two colored fluids (see, Fig. 2(b)).

The 2D flows are important due to their relevance in geo-physical, atmospheric, oceanography and fundamental hydrodynamics fields of research [11, 12]. The fundamental down scaling laws of hydrodynamics [22] justifies the use of micro-fluidic chip to model 2D turbid phenomenon relevant to formation of cyclones and warm/cold oceanic flows which all have *width/depth*$\simeq 10^2 - 10^3$ ratio as in a microfluidic chip 2 mm/20 μm = 100. We recently demonstrated that hydrodynamic scaling allows to compare laser induced material mass flow induced by micro-explosions [23] with their macro counterparts which have energies 10^{21} times higher and the space and time scales increased by 10^7 [24].

5. Conclusions

We demonstrate a simplified and versatile optofluidic platform where the channel is made in the adhesive film which is also used to assemble and hold the top and bottom plates of FP cavity. The channel was tested at high pressure corresponding to flow velocity up to 1 m/s and is capable for transport of comparatively large (10 ml) volumes in a reasonable operation time (5 min) required for actual certified drinking water tests. FP cavity of 25 μm width was reliably withstanding a high flow rate (high pressure) load during spectral measurements with a detection noise mainly caused by an uneven pressure of the peristaltic pump.

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