High Resolution Integrated Microfluidic Fabry-Perot Refractometer in Silicon

R. St-Gelais, J. Masson and Y.-A. Peter
Ecole Polytechnique de Montréal, Engineering Physics Department
P.O. Box 6079, Station Centre-Ville, Montréal (QC), H3C 3A7 CANADA
Email: {raphael.st-gelais, yves-alain.peter}@polymtl.ca
Tel + 1 514 340 4711 x 3100, Fax + 1 514 340 3218

***Abstract*—We present a high resolution, robust and low cost integrated refractometer for microfluidic systems. The device is made of two Bragg reflectors vertically etched in silicon to form an in-plane Fabry-Perot filter. Liquids are injected in the cavity through a microfluidic channel and the variation of the refractive index induces a shift of the resonance wavelength. A sensitivity of 920nm/RIU (Refractive Index Units) and a resolution of less than 10^{-3} are obtained and are in good agreement with optical simulations. This resolution is, to our knowledge, the lowest ever reported for an integrated microfluidic Fabry-Perot refractometer.**

I. Introduction

The measurement of the refractive index of gases and liquids has been an important field of research during the last century and still attracts a lot of attention since it is related to many physical parameters of materials. Recently, a lot of work has been done toward the integration of refractive index sensors to microfluidic systems [1]. Many sensors measure the interaction of an evanescent wave at the interface between the sample and a metal (surface plasmon resonance) or a dielectric (integrated wave guide, microcavities). These methods allow very high resolution measurements, sometimes better than 10^{-8}, but the interaction depth at the interface with the sample is typically smaller than 1μm, limiting the possibilities to measure the refractive index of bigger biological specimens such as cells. Single cell measurement is of great interest since it is low-cost, label free, and can be linked to the state or nature of a cell. For example, the effective refractive index can be related to the size and protein level of normal versus cancerous cells [2], or to the structure of a specific cell through the excitation of transverse modes in a Fabry-Perot cavity [3].

These applications require a Fabry-Perot cavity with mirror spacing of the order of a cell diameter, as well as integration to microfluidic systems. The proposed sensor fills these requirements and compares advantageously to similar devices [2], [4], [5], due to its simple fabrication, easy alignment, high resolution and robustness. The Bragg mirrors, microfluidic patterns and alignment grooves are fabricated simultaneously in one conventional microfabrication process. The grooves allow easy alignment of input and output fibers, which do not need any preparation steps such as reflective coating or splicing to collimating optics components. The length of the cavity can be designed from one to more than a hundred microns, depending on the targeted application. The measures yield high resolution and high sensitivity: $2 \cdot 10^{-3}$ and 920nm/RIU respectively, as well as great repeatability.

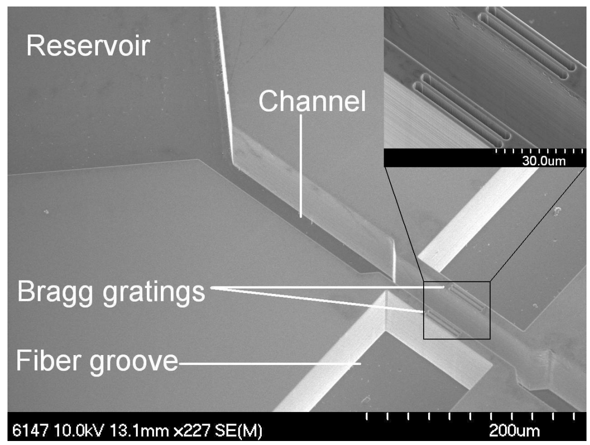


Fig. 1. SEM photograph of the Fabry-Perot sensor integrated with fiber alignment grooves, microfuidic channel and reservoir.

II. Sensor fabrication and principle of operation

The sensor is presented in Fig. 1. The whole structure is defined by a single photolithography step. The silicon is then etched by deep reactive ion etching (DRIE). The etch depth is 70μm to allow the use of 125μm diameter conventional SMF28 optical fibers. The low roughness and high verticality of the optical surfaces are ensured by optimization of the BOSCH process, as previously reported [6].

Liquids placed in the reservoir flow in the microchannel by capillary effect and reach the Fabry-Perot cavity formed by the two Bragg reflectors. Light from a broadband light source (1520nm - 1620nm) is incident on the Fabry-Perot through one of the optical fibers placed in the alignment grooves. The transmitted light is collected by the second optical fiber, which is connected to an optical spectrum analyzer.

Each of the Bragg reflectors is made of three layers of silicon and two layers of air. The photomask is designed with 2.6μm and 1.7μm thick walls for silicon and air respectively. These values will be modified by the fabrication process because of the diffraction effects through the small openings of the photomask and because of a typical 300nm undercut

978-1-4244-1918-0/08/$25.00©2008 IEEE

of silicon during the DRIE process. The length of the cavity (25μm) is chosen such that the phase shift experienced by the reflexion on a Bragg reflector is negligible compared to the phase shift experienced during a round trip in the cavity, thus improving the sensitivity of the device [7].

We can easily design a Fabry-Perot having a cavity of any length between one and more than a hundred microns. A smaller length would decrease the sensitivity and increase the free spectral range. This could be useful for applications where measurements are to be performed on a large range of refractive indexes. The flexibility of photolithography could also allow the variation of the microchannel width to trap cells in the Fabry-Perot cavity, for example.

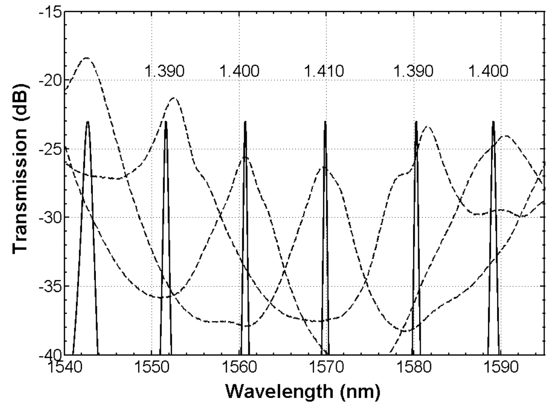
III. Results and discussion

The experimental and simulated results are presented in Fig. 2. The measurements are performed with certified refractive index liquids (Cargille Labs, series AA) with low temperature dependence (0.0004 RIU/°C). The simulated results are obtained by the transfer matrix method, considering a plane wave incident on perfectly parallel and flat surfaces [6]. Simulations considering the effects of a Gaussian beam and of verticality deviation of the walls could explain the transmission losses, as well as the broadening of the resonance peaks [8]. For now we approximate these effects by subtracting 23dB to the simulated results. The dimensions of the walls are measured in top view with a scanning electron microscope, showing an increase of about 1.1μm of the thickness of air layers caused by diffraction during photolithography. For the simulations, we also reduced the thickness of the silicon walls by 300nm at each interface to take into account the undercut of the DRIE process. These values are then slightly adjusted, respectively to 1.086μm and 314nm, to fit with the experimental results. Therefore, we propose that similar devices could be used as test structures to monitor precisely the thickness of vertically etched optical multilayers.

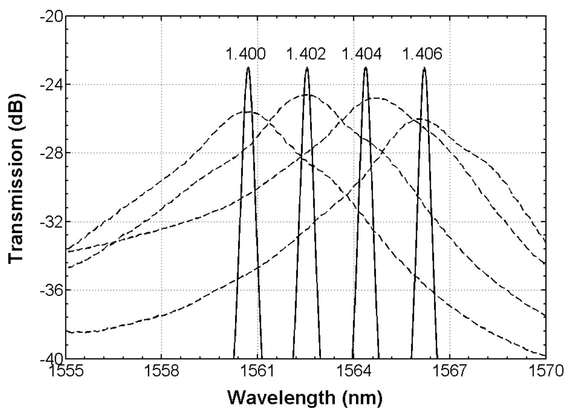
The sensor has a sensitivity of 920nm/RIU and was able to detect experimentally variations of $\Delta n = 2 \cdot 10^{-3}$ of the refractive index, as shown in Fig. 2 (b). For this value of Δn, the peaks were very easily distinguished. Therefore, a resolution of less than 10^{-3} can be reached. Such resolution is, to our knowledge, the highest ever reported for an integrated microfluidic Fabry-Perot refractometer. The sensor is very robust and produces highly reproducible measurements. The optical fibers were removed in order to clean the sensor with acetone and IPA between each measurement. This was done more than 30 times, out of cleanroom environment, and the sensor still produced the same spectrum for a given liquid.

IV. Conclusion

We reported a high resolution, robust and potentially low cost integrated microfluidic refractive index sensor in silicon. The sensor allows bulk refractive index measurement of liquids with a resolution of less than $\Delta n = 10^{-3}$ which is, to our knowledge, the lowest resolution ever reported for an integrated microfluidic Fabry-Perot refractometer. The integration of the sensor with microfluidic channels and reservoirs was demonstrated and might be of great interest in practical applications such as intracavity single-cell characterization [2,3].



(a)



(b)

Fig. 2. Measured (dashed lines) and simulated (plain lines) transmission of the Fabry-Perot filter filled with calibration liquids. The curves are labeled by the refractive index of the measured liquid. (a) Variation of the refractive index by $\Delta n = 0.010$. (b) Variation of the refractive index by $\Delta n = 0.002$.

References

[1] H. Hunt and J. Wilkinson, "Optofluidic integration for microanalysis," *Microfluidics and Nanofluidics*, vol. 4, no. 1, pp. 53–79, 2008.

[2] W. Song, X. Zhang, A. Liu, C. Lim, P. Yap, and H. Hosseini, "Refractive index measurement of single living cells using on-chip Fabry-Pérot cavity," *Applied Physics Letters*, vol. 89, pp. 203–901, 2006.

[3] H. Shao, W. Wang, S. Lana, and K. Lear, "Optofluidic intracavity spectroscopy of canine lymphoma and lymphocytes," *Photonics Technology Letters, IEEE*, vol. 20, no. 7, pp. 493–495, 2008.

[4] P. Domachuk, I. Littler, M. Cronin-Golomb, and B. Eggleton, "Compact Resonant Integrated Microfluidic Refractometer," *Applied Physics Letters*, vol. 88, p. 093513, 2006.

[5] H. Shao, D. Kumar, S. Feld, and K. Lear, "Fabrication of a Fabry–Pérot cavity in a microfluidic channel using thermocompressive gold bonding of glass substrates," *Journal of Microelectromechanical Systems*, vol. 14, no. 4, pp. 756–762, 2005.

[6] J. Masson, F. Koné, and Y.-A. Peter, "MEMS tunable silicon Fabry-Perot cavity," *Proceedings of SPIE*, vol. 6717, pp. 671–705, 2007.

[7] S. Weidong, L. Xiangdong, H. Biqin, Z. Yong, L. Xu, and G. Peifu, "Analysis on the tunable optical properties of MOEMS filter based on Fabry–Perot cavity," *Optics Communications*, vol. 239, no. 1-3, pp. 153–160, 2004.

[8] A. Lipson and E. Yeatman, "Low loss 1D photonic band gap filter in (110) silicon," *Opt. Lett*, vol. 31, pp. 395–397, 2006.