On-Chip Microfluidic Integration of Ultra-High Quality Silicon Optical Microdisk Resonators for Lab-On-Chip Applications

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Abstract

Silicon on insulator (SOI) technology platform enables the dense monolithic integration of planar nanophotonic optical components and electronic devices. Applying SOI technology to optical sensing, lab-on-chip applications can be envisioned that test for virtually any biomolecule. This project focuses on the design, fabrication, and testing of polydimethylsiloxane (PDMS) channels filled with varying refractive index oils that induce a shift in the resonance wavelength of ultra-high quality (Q) planar microresonators fabricated on SOI substrate, in order to create an effective biosensor. Detection of specific chemical and biological molecules through suitable selective surface coatings on such resonators allows for the rapid, inexpensive production of label-free sensor architectures for lab-on-chip systems [1].

Introduction

SOI substrates offer ultra-compact, ultra-high Q nanophotonic components that are completely compatible with silicon (Si) VLSI technology. Monolithic optical resonators in such SOI substrates, offer the further advantage of micron-scale size, and through suitable designs of the waveguide-cavity coupling, a complete 100% transmission of energy from the waveguide to the cavity is possible. Any molecule present over the resonator is sensed through the resonance wavelength shift induced by the refractive index of the molecule. Successful detection of indices leads to the development of an ultra-compact label-free biosensor.

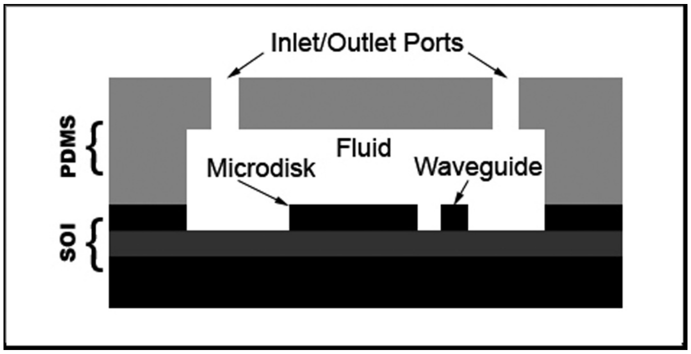

Figure 1: Resonator integrated with microfluidic channel. (Resonator radius: 20 µm, height: 230 nm.)

Experimental Procedure

SOI resonator chips were developed with several add-drop and single disk and ring resonators on each chip for comparison and finding optimal wavelength shifts. PDMS (Sylgard 184) fluidic channels with punched inlet and outlet ports were activated with O_2 plasma and aligned under a microscope to cover the resonators, ensuring index changes (Figure 1). Refractive index oils (Cargille Laboratories) ranging from index 1.32 through 1.395 were individually injected into the channel through a 23-gage polyethylene tubing (Intramedic Clay Adams) using syringes (Norm-Ject 5mL). Each micro-resonator covered with oil from the channel was evaluated for performance using a swept-wavelength test setup that recorded the resonances over a given group of wavelengths. The setup consisted of a tunable laser (Agilent Technologies Model 81680A, line width 100 kHz) for the wavelength sweep, a standard objective lens (Newport M-40x, 0.65NA) for input/output coupling to the device, followed by a photoreceiver (Thorlabs PDB 150C) that was interfaced to a personal computer through a data acquisition (DAQ) card (National Instrument PCI-6251, 16-Bit, 1 MS/s). All light coupled to the resonators used TE-polarized light (Figure 2).

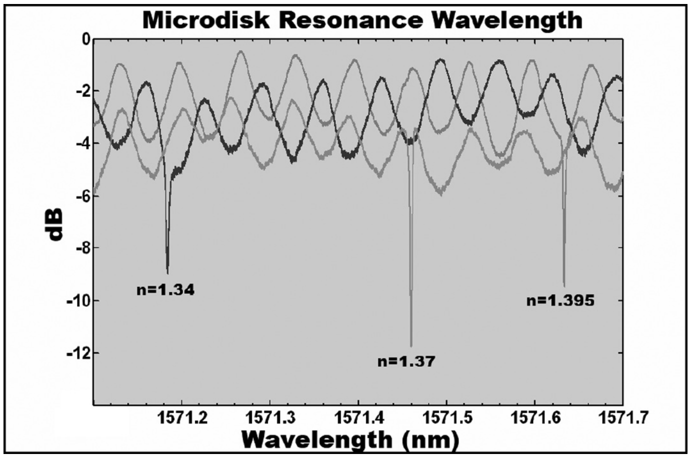

Figure 2: Microdisk spectral response.

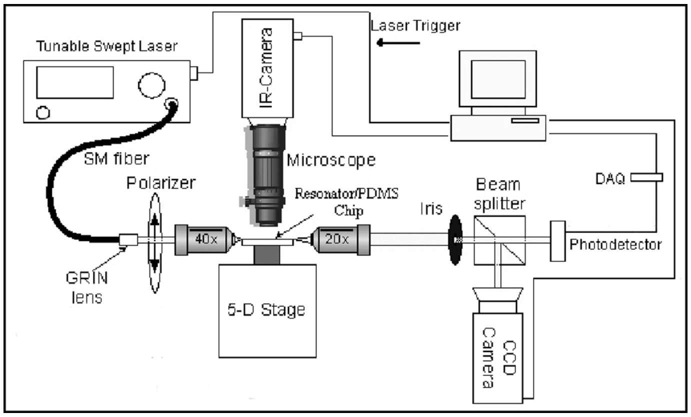

Figure 3: Test setup.

Initial tests of microdisk resonators yielded promising results with high quality factors ($Q > 10^6$; $Q = \lambda/\Delta\lambda$) and noticeable shifts between indices (Figure 3). Microrings, however, yielded greater shifts and were pursued in further tests due to the ease of detecting the index changes (Figure 4).

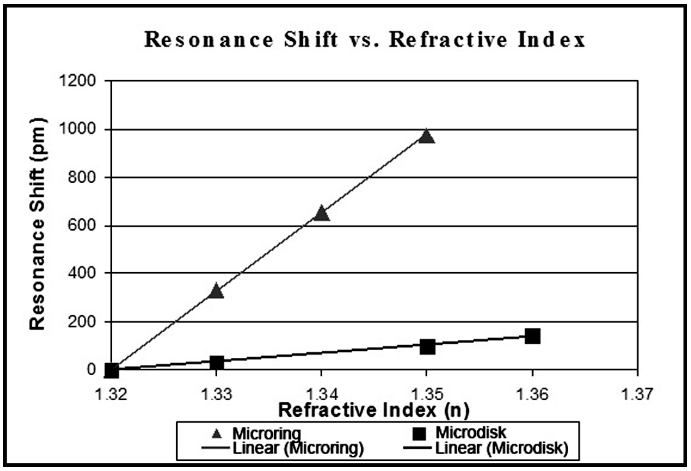

Figure 4: Resonator performance.

Some leaking was observed to come from the bottom of the channel, indicating a poor seal that resulted in a progressive difficulty in coupling the waveguides to the laser to begin the experiment. The imperfect seal resulted in a new channel designs with larger contact areas between the PDMS and Si. After new channel fabrication, real-time data acquisition methods were explored to simulate real-time detection. It was found that by applying a weight to an inverted syringe in a test tube rack (Lake Charles Manufacturing), gravity provided a linear flow rate in the range of 1 μL/s, suitable for further experimentation and easy index switching.

To rapidly identify indices in real-time, the DAQ program was revised to sweep 10 nm, thereby covering the free-spectral range of the resonator and hence capturing two resonances. Real-time detection resulted in 350 pm shifts between 0.01 index changes. Repeated measurements revealed that resonance wavelengths were consistent to within 1 pm, for the same index oil under flow conditions. However, it was observed during the real-time tests that the introduction of fluid flow, through applied pressure on the syringe, caused the resonance wavelengths to shift higher by up to 10 pm, when compared to the no-flow condition.

In order to understand this effect, we developed a complete model for the flow-channel under the external applied pressure. Initial results from this model indicate that the fluid pressure induced change in the oil index accounted for the shift. More detailed modeling of this effect is under further investigation.

Results and Conclusions

Early channels demonstrated the detection of a linear relationship between refractive index changes and resonance wavelengths over a given wavelength interval regardless of their type. Experimentation with ring resonators was pursued because their display of large shifts would provide for small index change identification. The second generation of channels allowed the development of a method of obtaining real time data. Given the high quality factors (10^6) observed from the resonators and that subsequent readings varied by less than 1 pm, index sensitivity was 2.85×10^{-5} for this device. With optimized device, wavelength shift of nanometers and detection on a picometer scale will be achievable for true lab-on-chip applications.

Future Work

At the time of this paper, microring resonators attached to micospectrometers are being fabricated for real-time lab-on-chip analysis function. Surface functionalization with biotin for testing with the highly specific protein Streptavidin in real-time is also being pursued for a biological approach. Future plans include multiple protein detection on the same chip as well as chemical sensing.

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References

[1] De Vos, Katrien et alia, "Silicon-on-Insulator microring resonator for sensitive and label-free biosensing," Opt. Express 15. 7610-7615 (2007).