On-chip switching of a silicon nitride micro-ring resonator based on digital microfluidics platform

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Abstract: We demonstrate the switching of a silicon nitride micro ring resonator (MRR) by using digital microfluidics (DMF). Our platform allows driving micro-droplets on-chip, providing control over the effective refractive index at the vicinity of the resonator and thus facilitating the manipulation of the transmission spectrum of the MRR. The device is fabricated using a process that is compatible with high-throughput silicon fabrication techniques with buried highly doped silicon electrodes. This platform can be extended towards controlling arrays of micro optical devices using minute amounts of liquid droplets. Such an integration of DMF and optical resonators on chip can be used in variety of applications, ranging from biosensing and kinetics to tunable filtering on chip.

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References and links


1. Introduction

The integration of optics and microfluidics, known as optofluidics, provides an attractive platform for the realization of optical devices with large variety of features and functionalities, including for example optofluidic dye lasers [1,2], switches [3,4], filters [5,6], sensors and biosensing devices [7–9], lenses [10] and optical microscopes [11].

One of the major advantages of integrating microfluidic technology with optical devices is the capability for adaptation and tunability of the optofluidic devices. Controlling the properties and the functionalities of the optical devices becomes feasible by introducing liquids with different refractive indices, absorption and gain coefficients, as well as by modifying the profile of the device [12–16]. Recently, we took advantage of this concept in order to demonstrate an optofluidic tunable polymeric microring resonator (MRR), where tunability is obtained by electrowetting actuation [17]. Herein, we develop a fabrication process that is compatible with high-throughput silicon fabrication techniques, and is based on a monolithic integration of silicon nitride optical MRR with a digital microfluidics (DMF) platform that allows an on-chip electrically controlled droplet manipulation [18–20] and demonstrate a micron-scale electrically controlled MRR device. The presented DMF system is based on the method of electrowetting on dielectric (EWOD) where the actuation electrodes are separated from the liquid by a thin insulating layer. In this configuration the electrowetting can be made stable for a long period of time by preventing hydrolysis of the droplet and irreversible degradation and pollution of the electrodes. Still, in EWOD method, the performance and the stability of DMF system is greatly affected by the quality and breakdown immunity of the insulating layer. Namely, a dielectric layer of better quality and higher breakdown voltage characteristic allows fabrication of a thinner insulator which in turn increases the capacitance (per unit area) between the surface and the droplet, and therefore enlarges the amount of electrowetting for a given applied voltage. For this reason, in this work we took advantage of CMOS process and replaced the standard metal electrodes with buried, highly doped silicon electrodes insulated by a high quality thermally grown oxide layer. This concept provides higher process flexibility and better compatibility with standard process flow. In addition, the use of silicon nitride waveguides allows the realization of smaller MRRs (~30 micron radius) compared to those demonstrated in our previous work. The implementation of thin device layer (nitride waveguide height is of 270 nm compared to ~2 microns in SU8 waveguides) diminish the problem of physical barrier for the translation of the droplets across the resonator. Finally, we chose to work at the wavelength of ~980 nm. This wavelength regime provides relatively low absorption of light in water and in parallel minimal damage to biological samples [21].

2. Operation concept

Our DMF system consists of a set of thin (~80 nm) highly-doped (n++) conducting silicon electrodes buried under a thermal oxide dielectric layer, which is covered by Cytop as a hydrophobic surface. Compared with other oxide layers (e.g. sputtered oxide or plasma enhanced chemical vapor deposited oxide) the thermal oxide serves as a good dielectric insulator which can hold higher field strengths before voltage breaking occurs (at the range of
25-40 Megavolts/meter). Our MRR consists of low-pressure chemical vapor deposition (LPCVD) silicon-nitride waveguides, providing high refractive index contrast and covering wide spectral regimes in both the visible and the infra-red. Typical waveguide dimensions are in the order of 900 nm wide by 270 nm thick to support a TE-like mode (in-plane polarization). The radius of the microring is 30 microns in order to minimize the bending loss of the resonator. More details about the design and the functionality of such MRRs can be found in Ref [22]. The device is encapsulated by an indium-tin-oxide (ITO) plate. ITO is chosen for its optical transparency, allowing observing the operation of the device under a microscope. The electrode layout for integrating the DMF with the photonic device is shown schematically in Fig. 1. By applying a specific sequence of voltages to the electrodes this structure facilitates a precise control over the droplet position allowing to change the medium above the MRR waveguides from air to liquid and vice versa. As a result, the effective refractive index of the MRR can be manipulated, thus providing the mechanism of electrical control over the resonance wavelength of the MRR. A schematic animation demonstrating the concept of operation of the device is shown in Media 1.

3. Design and fabrication

The fabrication process is depicted in Fig. 2. A Silicon-On-Insulator (SOI) chip (silicon thickness of 220 nm on top of a 2μm thick buried oxide) is used as a substrate. Firstly, the silicon layer was highly doped (ρ = 5.89x10^-4 Ωcm) with phosphor using a standard POCl₃ process (Fig. 2a). This layer will later be used as an electrode. Next, the electrodes pattern was defined by photo lithography (AZ1505 photoresist) and transferred to the highly doped silicon layer by short step of inductively coupled reactive ion etching (ICP RIE, fluorine-based chemistry) resulting with 80 nm deep trenches in the silicon layer (Fig. 2b). Then, an oxide layer was thermally grown over the highly doped silicon layer. The duration of this step was calibrated such that the electrodes pattern was transferred to the bottom of the silicon device layer, as shown in Fig. 2c. Next, we turned into the fabrication of the photonic device, in region which is slightly shifted from the DMF system and thus is free of electrodes (Fig. 2d). First, a 270 nm thick silicon nitride layer was deposited by LPCVD (Fig. 2e). The waveguides and the MRR were defined by electron beam lithography with 20 KV acceleration voltage and ZEP-520A as an electron-beam resist, following by an ICP RIE step with a CHF₃/O₂ gas mixture. The etching depth in the nitride was 205 nm, generating a rib-
like pattern with a rib height of 65 nm (Fig. 2f). Afterwards, the contact pads to the buried silicon electrodes were realized using an additional photolithographic step, following by a wet oxide etching in buffered HF solution in order to expose the silicon surface to the consequent metallization (Cr/Au, 5nm/50nm) by the lift-off process. To insure a hydrophobic surface for easier droplet translation all over the chip area, a thin (150 nm) Cytop layer was spin coated onto the chip (see Fig. 3 for the complete device micrograph). The device was enclosed by a glass top plate, coated by a 2μm thick transparent ITO layer and an additional 150 nm thick Cytop layer serving the purpose of obtaining a top hydrophobic surface. Finally, the device was set on the carrier and connected to external electrical contacts with Al wire bonding. In this configuration (see Fig. 4) the carrier shoulders were used as spacers, separating the ITO top plate from the bottom plate with a fixed gap of 700μm.

Fig. 2. Schematic description of the fabrication process. (a) Base material- highly doped SOI chip. (b) DMF’s electrodes are patterned by photolithography and transferred to the highly doped silicon layer by RIE. (c) Oxidation step insulates the electrodes from the top surrounding. (d) The photonic device substrate. (e) Silicon-Nitride layer is deposited by LPCVD. (f) Waveguides and MRR are patterned by Electron-Beam lithography, followed by nitride RIE.
4. Experimental setup

The experimental setup is depicted in Fig. 4:

Fig. 4. Experimental setup (top plate removed for visualization purposes). The lensed fibers are butt coupled to the waveguides. The DMF pads are wire bonded to the carrier pads to facilitate the connection to an external voltage source.
The device is operated by performing spectral transmission measurements using a tunable laser (Newport-Velocity) with spectral window of 965nm-995nm. This wavelength range is preferable over the telecom band because of the lower absorption of water. The light is launched into the bus waveguide and collected at the output by a polarization maintaining tapered fiber using a butt coupling configuration. The optical signal is detected by an InGaAs photodetector.

In order to control the position of the droplet we used 1KHz, 75V-peak AC signal generated by a function generator with a voltage amplifier. Once the droplet is positioned over a specific electrode, the actuation signal is addressed to the neighbored electrode, resulting in an effective surface tension gradient, which gives rise to the droplet translation toward the electrode under the bias. Upon applying a sequence of voltage signals, the droplet follows the addressed electrodes and move forward or backward. Typical sequence frequency is in the order of 10-20 Hz. An example of droplet translation over the electrode structure is shown in Media 2 (Fig. 5).

![Media 2]( electroode_structure.png)

5. Results

Figure 6a shows the transmission spectrum of the device with and without a droplet on top of the MRR. The effect of droplet position on the transmission spectrum of the MRR can be clearly observed. We obtained a resonance shift of ~2.4 nm, much larger than the linewidth of the resonance (~0.04 nm, corresponding to quality factor of ~25000). The maximal on-off ratio measured at a single fixed wavelength was ~12 dB. This value can be further improved by better matching the loss rate in the resonator to the coupling rate between the resonator and the bus waveguide, approaching the condition of critical coupling. One can also notice that the extinction ratio of the transmission curve is modified by the presence of the droplet. This can be attributed in part to the fact that the droplet modifies both the loss and the coupling rates of the MRR. Yet, it may also be the result of a limited scanning resolution of our tunable laser (~0.01 nm). To compare the measured resonance shift to the expected one we calculated the effective index of the optical mode with and without the droplet using finite element method (COMSOL). The accurate profile of the waveguide Cytop cladding was measured by atomic force microscope (AFM). The thickness of the Cytop was measured by a reflectometer. The simulated cross section of the waveguide is shown in Fig. 6b and the calculated mode profile is presented in Fig. 6c. From the computer simulations we expect the difference in effective index of the optical mode with and without water covering the top of the waveguide to be 0.033, corresponding to a wavelength shift of ~2 nm, slightly lower than
the measured resonance shift. The slight difference between the expected and measured resonance shift may be the result of a non homogenous Cytop layer.

Combining transport of liquids and optical resonances, our system may be useful for electrically controlled bio-sensing applications. For this purposes it is important to maximize the sensitivity (the shift in resonance wavelength normalized by the change in refractive index of the droplet) of the MRR. The sensitivity was simulated to be ~8.3 nm/RIU. Yet, it can be significantly improved by reducing the thickness of the silicon nitride layer and using a hydrophobic layer with a nanometric thickness. Recently, we demonstrated a silicon nitride MRR with sensitivity of 91 nm/RIU by using a thinner nitride with no hydrophobic layer [22]. Even higher values could be obtained by using a slot waveguide configuration. Another parameter is the Q factor. In general, the realization of high Q factor devices contributes to improved detection capability of the system due to the narrowing of the resonance linewidth, which in turn enables to detect smaller changes in resonance wavelength and thus allows observing smaller variations in the refractive index of the cladding material. The current Q factor (25,000) can be further improved by optimizing the parameters of the MRR and its fabrication process.

In addition to the spectral measurements we also measured the time response of device by applying a step function voltage to the electrodes and observing the evolution of the optical signal in time using an InGaAs photodetector (HP 81634B) and a 60 MHz oscilloscope. We found the response time to be in the order of 1-3 milliseconds. The time response measurement is shown in Fig. 6d. Further improvement in response time may be achieved.
through the shrinkage of the droplet size (currently in the 1 mm range), allowing increasing its mechanical resonance frequency. While this time response is relatively slow compared with electro-optic and thermo-optic approaches, this approach can be designed for operation at low electric power consumption. Similarly to the electro-optic effect, under DC operation conditions the electric energy that is applied to the circuit is stored in a capacitor (the oxide layer), rather than being converted to heat as in the case of thermal tuning. Therefore, as long as the droplet is held steady, power consumption is insignificant. Power consumption can become low also during the transient of the droplet from one state to another by reducing its dimensions, resulting in a significant reduction in its capacitance.

The real time operation of the device is demonstrated in Media 3 (Fig. 7). The droplet moves into and out of the MRR, resulting in a noticeable change in its optical transmission. In addition, the electromagnetic energy inside the MRR can be clearly observed once the droplet is moving away from it, as a result of the MRR being tuned to meet the resonance condition.

![Fig. 7. Frame excerpts from Media 3. The media shows the real time operation of the device. The droplet moves into/out the MRR top, bringing the MRR to/from resonance, which can be clearly seen at the media. (a) The droplet does not cover the MRR, resonance condition is obtained. The output signal is weak. Light scattering from the MRR can be observed. (b) The droplet moves and cover the MRR which is now not in resonance. As a result, stronger output signal is observed. Light scattering from the MRR can be no longer observed.](image)

6. Conclusions

In conclusion, we have exploited the platform of digital microfluidics to demonstrate the switching of a silicon nitride micro-resonator by electrically controlled signals. Resonance shift of ~2.4 nm and time response in the millisecond range was observed. The device was fabricated using a process that is compatible with high-throughput silicon fabrication techniques. Highly doped silicon electrodes were used to facilitate the DMF operation. The demonstrated platform can be further extended to include an array of micro resonators, and arrays of droplet traveling on top of the resonators. Such a system may be useful for electrically controlled biosensing as well as for switching and filtering applications.

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