A MICRO-FLUIDIC-OPTICAL SWITCH USING MULTI-DROPLET RESONATORS ARRAY

Y. F. Yu\textsuperscript{1,2}, T. Bourouina\textsuperscript{2}, and A. Q. Liu\textsuperscript{1}

\textsuperscript{1} School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore, 639798
\textsuperscript{2}Ecole Supérieure d'Ingénieurs en Electronique et Electrotechnique, University of Paris Est, France, 93162

(Email: eaqliu@ntu.edu.sg, Tel: +65-6790-4336, URL: http://nocweba.ntu.edu.sg/laq_mems/)

ABSTRACT
This paper presents a micro-fluidic-optical switch via side coupling multi-droplet resonators to an optical waveguide. The optical switch consists of a Polydimethylsiloxane (PDMS) waveguide, a T-junction for oil droplets generation and two optical fibers for light detection. The states of the optical switch are determined by the resonant modes and the distribution of the droplets. Compared to the solid optical resonator switch, the micro-fluidic-optical switch has various advantages, such as wide wavelength tuning range, easy fabrication process, simple manipulation, and low cost. The diameters of the droplets generated are within the range of 20 µm to 50 µm.

KEYWORDS
Droplet resonator, PDMS waveguide, T-junction

INTRODUCTION
Optical switch is a significant component in optical communication. Side coupling micro-droplet/ring resonators to signal waveguide is well known in narrow band and large free spectral range optical switches [1, 2]. Compared to the Fabry-Pérot resonator based optical switch, solid micro-droplet/ring resonator based optical switch has a smaller parameter varying range [3]. Droplet resonator based optical switch can overcome such problem. Micro-fluidic system provides a continuous droplets array, with a large varying droplet periods and wide diameter tuning range [4]. When these two core systems are integrated together, a micro-fluidic-optical switch is obtained. Compared to the mechanical optical switch, the micro-fluidic-optical chip has an infinite working time.

In single phase micro-droplet, evaporation, disturbance and stabilization are the main challenges [5]. Multiphase droplets formed by two immiscible liquids are able to prevent the evaporation of the droplets. In addition, the micro-scale structures and the laminar flow in the microfluidic chip can avoid large disturbance. Finally, the stabilization is determined by the flow conditions. The diameters have a deviation of 5% for large number of droplets with the same flow conditions [3]. Stable pressure driving micro-fluidic system is applied in this paper to achieve a smaller diameter deviation. Another challenge for the system is to stop the droplets. In this paper, vacuum driven technology is applied on the outlet, which can stop the droplets array fast and steadily.

Several methods are used to couple light into droplet/ring resonators [6-8]. Free space coupling is used by shining light beam directly on the droplets but the coupling efficiency is low. Fiber taper is used in phase-matched waveguide light coupling to couple input light and resonant modes by evanescent wave [5]. Compared to the free space coupling, it has higher coupling efficiency and low loss. However, a control system with a piezoelectric driver, which is used to adjust the nano gap between the resonator and the fiber taper, complicates the manipulation of the integrated detection devices. In this paper, PDMS waveguide coupling method is used to couple light into the droplets resonator. It demonstrates higher efficiency than the free space coupling and avoids complicated manipulation.

Figure 1: (a) Schematic of optofluidic chip with optical detection and (b) switch region.

DESIGN AND ANALYSIS
The micro-optic-fluidic chip consists of two liquid inlets, a waste outlet, a T-junction, an enlarged channel region and two integrated optical fibers, as shown in Fig. 1(a). Two immiscible liquids are pumped into the microchannel from the inlets separately. Due to the shear stress, the multiphase plugs are generated by the T-junction in the chip. These plugs are reformed into droplets due to surface tension at the beginning of enlarged channel region. The micro-fluidic-optical switch is shown in Fig. 1(b). The two optical fibers are aligned along the PDMS waveguide, to couple light in and out of the waveguide. The PDMS waveguide is formed in between the microchannel using the U-shape channel structure, such that it guides the droplets to...
move along the sides of the PDMS waveguide. The resonant modes are determined by the diameters of droplets in the channel.

When the gaps between the droplets and the PDMS waveguide are larger than 2 µm, light can pass through the optical switch efficiently. It is indicated as an ‘on’ stage. When the gaps are smaller than 2 µm, light, which has the same frequencies as the resonant modes of droplets, is blocked because it is coupled into the droplets and lost into the free space. This is indicated as an ‘off’ stage, as shown in Fig. 2.

At the off state, the switch is formed by two sets of side-coupled integrated resonator array. The resonant wavelengths of the optical switch depend on the diameters of the droplets. If these droplets have the same diameters, the blocked wavelengths $\lambda_n$ (n-order) can be expressed as following [6]:

$$\lambda_n = DN\pi/n$$  \hspace{1cm} (1)

where $n$ is the mode number, $N$ is the refractive index of droplets and $D$ is the diameter of the droplets. If these droplets have different diameters, more different wavelengths of light are blocked. Therefore, the free spectrum range of n-order mode of switch, $T_n$, can be deduced as:

$$T_n = \frac{\lambda_n^2}{D\pi N - \lambda_n}$$  \hspace{1cm} (2)

Several methods can be used to change the switch state based on Eq. (1). The refractive index of the droplets can be changed using different solutions to form the droplets. In order to switch states quickly, another T-junction must be induced. A convenient method is to change the diameter of the droplets by tuning the flow conditions. Defect in the droplets array can also change the state of the switch, i.e. change in the size or the refractive index of one droplet in the droplet array [7].

The micro-fluidic-optical switch is simulated by finite-difference time-domain (FDTD) method. The resonant modes are determined by simulating the resonator array with a pulse light source. A resonant wavelength (1261 nm) is selected to simulate the energy distribution, as shown in Fig. 3. Based on the simulation results, when light passes through the PDMS waveguide along the arrow in the central waveguide, most energy is trapped in the droplets and lost into the free space and some of the energy is coupled into the PDMS walls on the top and the bottom. The Q-factor of the droplet resonators depends on the input leakage ($Q_I$), the absorption ($Q_{abs}$) and the radiation loss ($Q_{rad}$) in the cavity, and the output rate ($Q_O$) [5]:

$$\frac{1}{Q} = \frac{1}{Q_I} + \frac{1}{Q_{abs}} + \frac{1}{Q_{rad}} + \frac{1}{Q_O}$$  \hspace{1cm} (3)

Both the input leakage and the output rate depend on the light coupling method used. In this paper, $Q_I$ is the major limitation.

**EXPERIMENTS AND RESULTS**

Figure 4 shows the PDMS chip, which is fabricated using standard soft lithography and bonded with glass substrate using surface plasma treatment. The optical fibers are inserted into the chip through the channels patterned in the chip for light input and output. The PDMS waveguide is fabricated by two kinds of PDMS with different refractive indices. The core is pure PDMS with the refractive index of 1.41 and the cladding is the mixture of PDMS and silicon oil with the refractive index of 1.40. After thermal curing, the cladding PDMS mixture is poured on the mold again. The single mode fiber is used as the input fiber and the multi mode fiber is used as the output fiber for better coupling efficiency. The width of the PDMS waveguide is 30 µm and the height is 50 µm. They are both smaller than the diameter of the core of the multi mode fiber (65 µm).

The two immiscible liquids are 70% ethanol solution (RI =1.362) and immersion oil (RI = 1.452), which are used to form multiphase droplets at the T-junction. Due to their different surface tensions and the hydrophilicity of the PDMS surface, the contact angle of immersion oil plugs is larger than 90° as shown in Fig. 5(a). The oil plugs shrink into droplets at the beginning of enlarged channel region. At flow velocity, if the droplet is smaller than the channel height (50 µm), the droplets are perfect spheres because the gravitational effect is negligible. When the flow is fast, the shape of droplets is deformed to coincide with the shape of the velocity profile. Small deformation will not affect the light confining capability of the droplets. Based on the
experiments, when the flow velocity is smaller than 5 mm/s, the deformation does not affect the resonance. The droplets (D = 25.2 µm) pass through the channel along the sides of the PDMS waveguide is shown in Fig. 5(b). Optical switch with smaller (D = 20.5 µm) droplets and longer period is shown in Fig. 5(c).

The superluminescence light emitting diode (Denselight, DL-CS2079A) with a central wavelength of 1275 nm and a bandwidth of 70 nm is used as the light source and the optical spectrum analyzer (Advantest, Q8384) is used for the transmission spectrum measurement. Fig. 6 illustrates the transmission spectrum at different states. The black solid line is the spectra of switch without oil droplets, which is used as the reference. The dash line is the spectra of the switch with the droplets of diameter 25.2 µm, corresponding to Fig. 5(b). The dotted line is the spectra of the switch with the droplets of diameter 20.5 µm, corresponding to Fig. 5(c). From the results, we can see that the resonant wavelength of 1238 nm is switched by changing the diameter of the droplets.

CONCLUSIONS

In summary, a micro-fluidic-optical switch using a multi-droplet resonator array is demonstrated for different switch states. The resonant wavelengths of the switch are tunable. These properties bring out the potential of this optical switch in cell sorting, disease diagnosis, optical communication, and optofluidic integrated circuits etc.

REFERENCES