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An On-Chip Micro-Droplet Optical Filter Using Evanescent Wave Coupling

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Abstract. An on-chip micro-droplet optical filter based on the evanescent wave coupling by fiber taper is presented in this paper. The optical filter consists of a T-junction for micro-droplets generation and an integrated optical fiber taper for light input and output. The light is coupled into the droplet resonator when it has the same wavelengths as the Whispering Gallery Modes (WGMs) of the droplet. The coupling efficiency can be adjusted by tuning the distance between the droplet and the fiber taper using micro fluidic flow. Compared with the solid sphere or ring optical filter using fiber taper coupling, the diameter and refractive index of liquid droplet can be easily tuned, which means the resonant modes can also be tuned. The diameter of the droplet is controlled by the flow rate ratio at the T-junction. The micro-droplet optical filter also has advantages as wide wavelength tuning range, easy fabrication process, simple manipulation, and low cost, which promise for many applications in optical analysis on micro-optical-fluidic chip.

Introduction

Optical filter based on the resonator modes of silica ring or solid sphere attracts more attentions because of its narrow linewidth and high Q-factor [1-5]. Micro-optical-fluidic chip is current hot point due to its small volume of sample and high efficiency [6, 7]. The on-chip micro-droplet optical filter is the combination of the two systems, which has the heritable features as mentioned. Due to the combination, the micro-fluidic system can provide droplet cavity with large variations in diameter and refractive index, which means the filter has new features as wide wavelength tuning range and simple manipulation. The Polydimethylsiloxane (PDMS) chip fabricated by standard soft lithography has features as low cost and deposable.

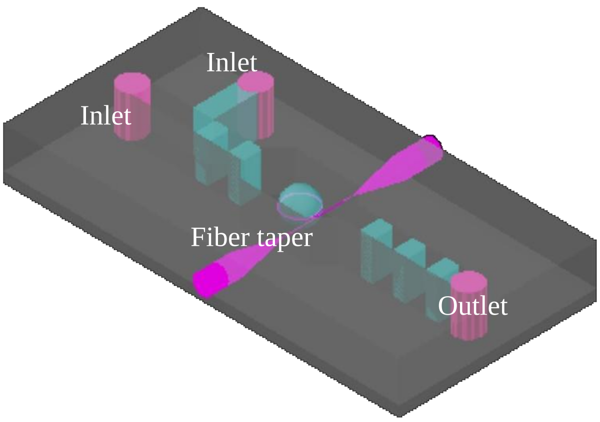


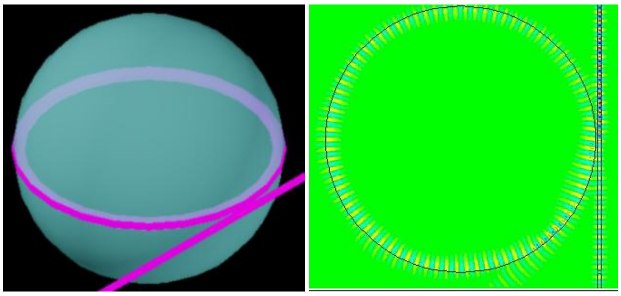
Figure 1. Schematic of the single droplet carrier with optical detector.

This optical filter consists of a T-junction for micro-droplets generation and an integrated optical fiber taper for light input and output, as shown in Fig. 1. Compared to the levitated droplet [8] and the sessile droplet [9], the multiphase droplet has high stability and can work continuously. The light coupling using fiber taper has high efficiency compared to free space light coupling.

Theoretical Analysis

The multiphase micro-droplet formed by two imisible liquids is a pefect spherical cavity because that it has ultra high smooth interface caused by the interfacial tension, and the effect of gravity is negligible due to the microscale diameter and the flotage. In such a cavity, the light propagates in the form of Whispering Gallery Modes (WGMs) resulting from the total internal reflection of the light along the curved interface. Based on the solution of Maxwell's equations, the evanscent WGM field has distance as [10]:

$$r = \lambda/[2\pi(\varepsilon\mu\text{-}1)^{1/2}] \tag{1}$$



(a) (b)

Figure 2. (a) 3D schematic; (b) 2D simulation of the fiber taper waveguide coupling.

where λ is the wavelength, ε is the relative permitivity and μ is the relative permeability. For most material μ is close to 1 at optical frequencies, so the distance is determined by λ and ε . The refractive index (RI) of droplet n_s and surrounding medium n_a can be presented respectively as $n_s = \varepsilon_s^{1/2}$ and $n_a = \varepsilon_a^{1/2}$, where ε_s is the permitivity of droplet and ε_a is the permitivity of surrounding medium. The relative permitivity of the multiphase droplet ε equal to $\varepsilon_s/\varepsilon_a$. The equ. (1) can be represented as following.

$$r = n_a\lambda/\{2\pi[\,(n_s\text{-}n_a)(n_s\text{+}n_a)\,]^{1/2}\} \tag{2}$$

The refractive index of droplet should be higher than the refractive index of surrounding medium ($n_s > n_a$) for effecient light confinement. Higher refractive index of surrounding medium means longer distance of the evanscent WGM field. For TM mode, the eigenfrequencies of WGMs of droplet has the expressions as [10]:

$$\omega_n \approx \frac{c}{a(\varepsilon\mu)^{1/2}}\left[v + 1.85576v^{1/3} - \frac{1}{\varepsilon}\left(\frac{\varepsilon\mu}{\varepsilon\mu - 1}\right)^{1/2} + o\left(v^{-1/3}\right)\right] \tag{3}$$

where n is mode number, c is the speed of light, a is radius of the droplet, $v = n+1/2$, and the symbol o($v^{-1/3}$) means the terms omitted are of the order of $v^{-1/3}$. The free spectrum range (FSR) T_n of WGM s can be presented as

$$T_n = 2\pi c\left|\frac{1}{\omega_{n+1}} - \frac{1}{\omega_n}\right| \tag{4}$$

where λ_n is the wavelength of n-order WGMs.

Figure 2 shows that the light from the fiber taper is coupled into the single droplet by evanescent wave. The whispering gallery modes in the droplet are coupled out by the fiber taper as shown in Fig. 2(a). Based on the simulation results, the distribution of electric field intensity is observed in Fig. 2(b), in which most of the energy is trapped at the edge area of the droplet due to the higher refractive index.

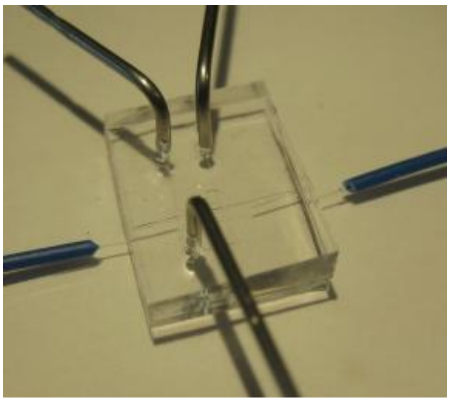


Figure 3. Photo of the PDMS chip.

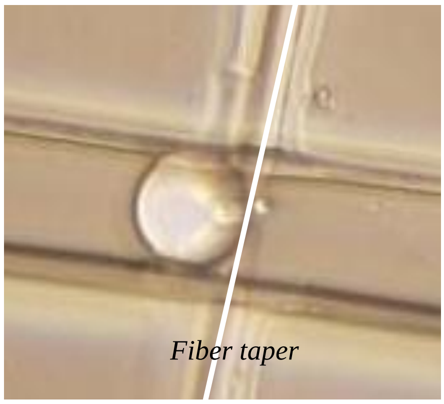


Figure 4. The top view the oil droplet and the fiber taper in the channel.

Experiments and Results

Figure 3 shows the PDMS chip, which is fabricated using standard soft lithography. Two PDMS slabs are bonded together after alignment and surface plasma treatment. The fiber taper is located in the chip after bonding and three metal tubes are used for inlets and outlet.

Two immiscible liquids are pressed into the micro channel from the inlets separately. The channel is of 50 µm height and 40 µm width at the T-junction. Due to the shear stress caused by the velocity mismatch, the multiphase plugs are generated by the T-junction, and these plugs are reformed into droplets due to the surface tension at the beginning of enlarged channel region (width 100 µm). These droplets have diameters ranging from 20 µm to 50 µm correspond to different flow rate ratio of two inlets. The fiber taper is stretched on flame and has diameter around 3 µm. It is sandwiched by two PDMS slabs and is crossed over the microchannel. Different FSR are observed when different droplets are nearby the fiber taper. The variable pressure which is used to driven the flow can be used to manipulate the droplet and to stop it at any place in the channel.

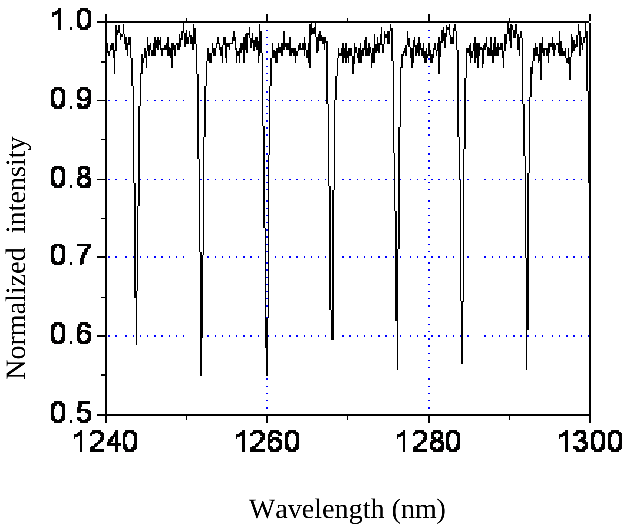


Figure 5. The transmission spectrum of optical filter.

Figure 4 is the top view of the oil droplet and the fiber taper. When the oil droplet is in vicinity to the fiber taper, light is coupled into and out of the droplet. Immersion oil (RI = 1.451) and ethanol solution (RI = 1.362) are used as the two immiscible liquids for droplet generation. Due to the different hydrophilicity, the oil shrinks into droplet and the ethanol solution fills the channel as the surrounding medium.

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. The transmission spectrum of optical filter is shown as Fig. 5. The resonant modes and the FSR of the transmission spectrum coincide with the theoretical estimation using (3) and (4).

Conclusion

An on-chip micro-droplet optical filter is designed and demonstrated in this paper. The single droplet generated by the T-junction has large diameter variation range, which provides wide wavelength tuning range. The micro-droplet optical filter also has advantages as easy fabrication process, simple manipulation, and low cost, which promise for many applications in optical analysis on micro-optical-fluidic chip.

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