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Microfluidic Flowmeter Based on Liquid Crystal Filled Nested Capillary

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Microfluidic flowmeter based on liquid crystal filled nested capillary

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ABSTRACT

A novel flowmeter composed of a liquid crystal-filled nested capillary is proposed and experimentally demonstrated. Whispering gallery modes (WGMs) in the nested capillary are excited by a tapered fiber coupled perpendicularly to the nested capillary. The WGM transmission spectrum of the fiber taper was optimized to achieve the highest possible quality (Q) factor by moving the capillary along the axis of the fiber taper. The air flowing through the capillary cools it down, which leads to a temperature-induced change of the refractive index of the nematic liquid crystal. This change in turn leads to a spectral shift of the WGM resonances, which can be linked to the airflow speed in capillary. A sensitivity of 0.242 nm/sccm has been demonstrated in our experiment. The proposed sensor provides a new platform for WGM flowmeters and offers the advantages of high sensitivity and miniature size.

Keywords: Whispering gallery modes, capillary resonator, liquid crystal, flowmeter

1. INTRODUCTION

With the development of micro fabrication technology, microfluidic devices and sensors have been extensively studied for applications in biological sensing [1], chemical reactions detection [2] and particle screening [3]. Microfluidic platforms require small sample volumes allowing to greatly decrease waste of the analytes, which makes it attractive for many applications including air or liquid metering. In recent years, microfluidic flowmeters integrated with fiber optics have attracted a lot of attention and several novel structures have been proposed and demonstrated. Yan *et. al* presented a microfluidic flowmeter by wrapping a microfiber coupler around a gold film coated capillary [4]. Liu *et. al* proposed a stacked capillary flowmeter sensor based on a microfiber Bragg grating (FBG) connected with Co^{2+}-doped optical fiber [5]. The liquid flow in the capillary was used to adjust the temperature of the stacked FBG. However, the complexity of fabrication of the device led to multiple challenges in its application in practice.

Due to the advantages of high sensitivity and small volume, whispering gallery modes (WGM) resonator-based flowmeters have been extensively studied and a variety of flow sensors have been proposed and demonstrated. For example, a capillary flowmeter integrated with a dye-doped polymer with a sensitivity of 17 pm/sccm has been reported in [6]. The shift in the laser peak wavelength reflected the flow rate due to temperature variations caused by the air flow. Another flowmeter utilized cooling effect of the gas flow within a the Er:Yb doped capillary resulting in the laser wavelength shift towards shorter wavelength [7]. However, a laser source had to be used to trigger the WGM laser, and a relatively high cost on the instrument potentially limits its practical applications.

In this paper, we demonstrate a novel flowmeter structure based on nested cylindrical WGM resonators, one of which is filled with a liquid crystal (LC), where the WGM modes are excited using a tapered fiber placed perpendicularly to the outer capillary. The device was fabricated by tapering two nested capillaries with different diameters using the microheater brushing technique. The flowmeter function was realized due to the change in the refractive index (RI) of the liquid crystal filling the surrounding larger capillary, caused by the air flow through the inner smaller capillary. The sensitivity of the WGM spectrum to the airflow speed in our experiment was 0.242 nm/sccm. To the best of our knowledge, this is the first attempt to use the temperature response of the liquid crystal to realize a flow sensor. The proposed scheme shows the advantages of high sensitivity and miniature size, with many potential practical applications.

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2. EXPERIMENTAL SETUP AND SAMPLE PREPARATION

Nested thin-wall capillary was fabricated by tapering two capillaries with different diameters using the customized microheater brushing technique [8]. In our experiment, the polymer coating layer of a commercial silica capillary (Polymicro Technology) with the outer/inner diameters of 435 μm and 320 μm respectively was stripped off and then a short section (15 cm) of the stripped capillary was inserted into another silica capillary (Polymicro Technology) with the outer/inner diameters of 850 μm and 700 μm to form the nested capillary structure. The two ends of the nested capillary were then fixed to the computer-controlled stages and the center of the nested capillary was stripped off its coating and placed in the slit of a ceramic microheater where the temperature was approximately 1300 °C. The customized computer system was to make sure that the center of the nested capillary was heated and tapered simultaneously to achieve the final diameter of 60 μm and 30 μm for the outer capillary and inner capillaries, respectively. The fabricated nested capillary was then fixed on a glass substrate using two drops of UV glue. Figure 1 is a microscopic image of the nested capillary.

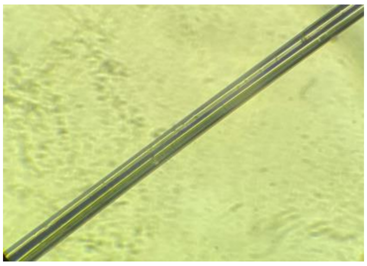

Figure 1 (a) Microscopic image of the nested capillary structure, (b)&(c)

The tapered fiber with a uniform waist diameter of 1 μm was prepared using the same microheater brushing set-up. The two ends of the tapered fiber were connected to the broadband light source (Thorlabs, 1500–1600 nm) through a polarization controller and the optical spectrum analyzer (OSA, Advantest, Q8384). For light coupling, the nested capillary fixed to a translation stage was placed in contact with the uniform waist region of the tapered fiber. Then, the nested capillary was gradually moved along the fiber taper axis until the WGM spectrum with the highest possible Q-factor was observed.

Two drops of UV glue were applied to the substrate to fix the relative position between the tapered fiber and nested capillary. Finally, the empty volume between the outer and inner capillaries was filled with a nematic liquid crystal (MDA-05-2782, n_e =1.6152, n_o =1.4912, measured at 589.3 nm and 20 °C, clearing point: 106°C) (Licristal, Merck) using a syringe from one end of the nested capillary. The schematic diagram of the proposed flow sensor is shown in Figure 3. Finally, one end of the inner capillary was connected to an air pump (YZ1515, Baoding Qili constant Pump, Co.), which provides the air flow with different sccms (mL/min).

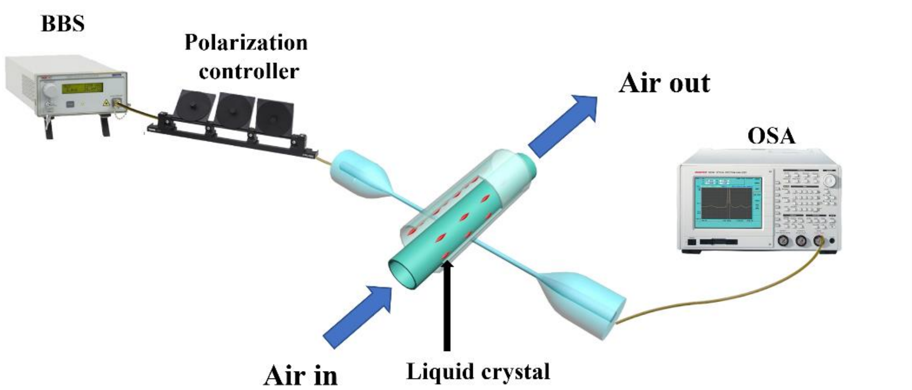

Figure 2 Schematic diagram of the nested capillary-based flow sensor and experimental setup for its characterization.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3(a) shows a schematic diagram of coupling between the nested capillary to the tapered fiber at different points ***a***, ***b*** and ***c***. Figure 3(b) shows the corresponding transmission spectra when the nested capillary was coupled at points ***a, b*** and ***c***. As can be seen from the figure, higher extinction ratio WGM dips with higher Q factors appeared as the nested capillary moved along the axis of the tapered fiber. The highest Q factor is calculated as $1.47*10^3$ by analyzing the WGM resonance near 1549.2 nm, where the full width at half maximum (FWHM) is measured as 0.108 nm, as shown in Figure 3(c).

Figure 4(a) shows the transmission spectra of the nested capillary resonator corresponding to different flow rates. As can be seen from the graph, the WGM resonance wavelength increases in a non-linear fashion as the flow rate increases. Figure 4(b) illustrates the dependency of the selected wavelength resonance (near 1551.8 nm) versus the flow rate of the pump. The resonance wavelength firstly increases as the flow rate increases, while further increase in the flow rate from 2 to 3.5 sccm leads to the wavelength approaching saturation. This result can be explained by the temperature dependence of the refractive index of the LC. As the air flows through the inner capillary, it cools down the liquid crystal material causing the increase of its effective RI and results in the red shift of the WGM spectrum. A faster air low speed leads to a more significant change in the RI and thus a greater spectral shift. It should be noted that the temperature dependence of the LC is nonlinear, which results in the observed saturation of the spectral shift at higher air flow speeds.

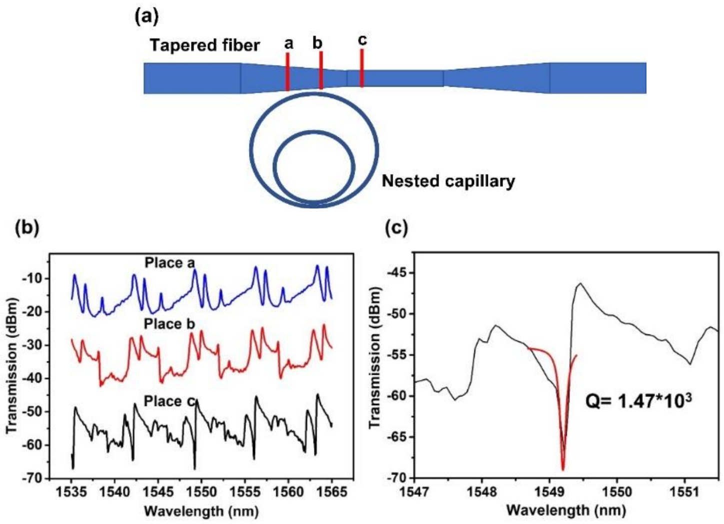

Figure 3. (a) Schematic diagram of the nested capillary coupled to the tapered fiber, (b) the corresponding transmission spectra of the nested capillary, (c) the transmission spectrum of the resonator coupled at point ***c*** in the wavelength range of 1547 nm to 1551.5 nm.

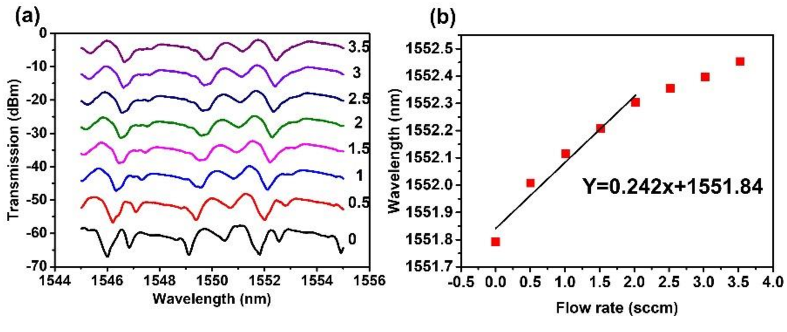

Figure 4. (a) Measured transmission spectra of the LC filled nested capillary, (b) selected spectral dip versus the flow rate.

To establish the influence of the LC on the proposed flow sensor, a similar experiment was carried out for the nested capillary structure without filling it with the LC. Figure 5(a) shows the spectral response of the resonator at different flow rates. Figure 5(b) shows the dependency of the of the selected wavelength resonance (near 1535.5 nm) versus the flow rate of the pump for the nested resonator where the LC was replaced by air. As can be seen from figure 5(b), the resonance dip experiences a very small blue shift with the increase of the flow rate, which can be explained by the diameter change of the capillary under the smaller pressure due to the air flow.

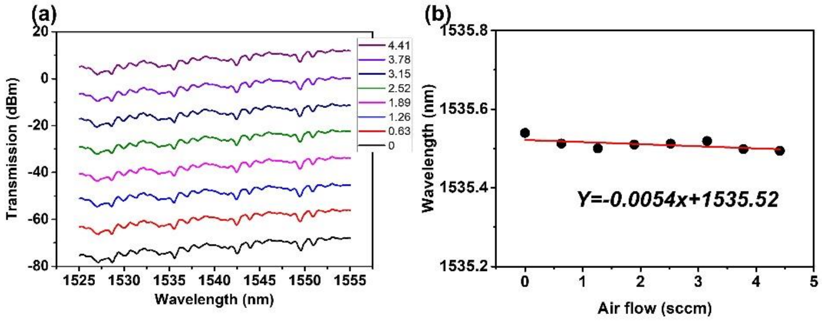

Figure 5. (a) The transmission spectra of the nested capillary resonator without LC filling, (b) the selected spectral dip versus the flow rate.

4. CONCLUSION

A novel flowmeter based on a liquid crystal- filled nested capillary has been proposed and experimentally demonstrated. The WGMs were excited in the capillary by coupling light from the tapered fiber placed perpendicularly to the capillary. The shape of the fiber taper transmission spectrum changed when the light coupling position was adjusted by moving the nested capillary along the tapered fiber axis, with the highest Q factor of $1.47*10^3$ achieved in the experiment. A nematic liquid crystal (MDA-05-2782) was studied as the thermo-optic sensitive filling material for the nested capillary flow meter. Spectral shift of the WGM resonances in the spectrum of the fiber taper was demonstrated when the air was passed through the inner capillary due to the temperature -induced changes of the nematic LC RI caused by the cooling effect of the air flow. A flowmeter with the sensitivity of 0.242 nm/sccm has been demonstrated in the experiment. To demonstrate the importance of the nematic LC, similar experiment using an air-filled nested capillary was carried out, which resulted in a 45 times smaller wavelength shift. The proposed sensing structure has the advantages of high sensitivity to the air flow speed and can be potentially used in many applications.

REFERENCES

[1] Whitesides, G. M., “The origins and the future of microfluidics,” Nature 442(7101), 368–373 (2006).
[2] DeMello, A. J., “Control and detection of chemical reactions in microfluidic systems,” Nature **442**(7101), 394–402 (2006).
[3] Chaipan, C., Pryszlak, A., Dean, H., Poignard, P., Benes, V., Griffiths, A. D. and Merten, C. A., “Single-Virus Droplet Microfluidics for High-Throughput Screening of Neutralizing Epitopes on HIV Particles,” Cell Chem. Biol. **24**(6), 751-757.e3 (2017).
[4] Yan, S., Liu, Z., Li, C., Ge, S., Xu, F. and Lu, Y., “‘Hot-wire’ microfluidic flowmeter based on a microfiber coupler,” Opt. Lett. **41**(24), 5680 (2016).
[5] Liu, Z., Tse, M.-L. V., Zhang, A. P. and Tam, H.-Y., “Integrated microfluidic flowmeter based on a micro-FBG inscribed in Co^2+-doped optical fiber,” Opt. Lett. **39**(20), 5877 (2014).
[6] Niu, B., Shi, X., Ge, K., Ruan, J., Guo, D. and Zhai, T., “Microfluidic flowmeter based on tunable polymer WGM laser,” Org. Electron. 107(April), 106563 (2022).
[7] Ward, J. M., Yang, Y. and Nic Chormaic, S., “Glass-on-Glass Fabrication of Bottle-Shaped Tunable Microlasers and their Applications,” Sci. Rep. **6**(1) (2016).
[8] Wang, Z., Mallik, A. K., Wei, F., Wang, Z., Rout, A., Wu, Q. and Semenova, Y., “Thermo-optic tuning of a nematic liquid crystal-filled capillary whispering gallery mode resonator,” Opt. Express **29**(15), 23569 (2021)