A Liquid-core Liquid-cladding Optical Waveguide Based on Thermal Gradients across the Laminar Flow of Water in Capillary Tubing

Manami NAKAMURA, Hiroyasu MURATA, Kiichi SATO, and Kin-ichi TSUNODA†

Department of Chemistry and Chemical Biology, Gunma University, Tenjin-cho, Kiryu 376-8515, Japan

A liquid-core liquid-cladding optical waveguide based on thermal gradients across laminar flow was built with the laminar flow of water in a stainless capillary tube placed in a heat source. Its characteristics were studied with both experiments and a computational fluid dynamics simulation, firstly showing that it had the nature of a graded index optical fiber.

Keywords A liquid-core liquid-cladding optical waveguide, thermal gradients, laminar flow, water, graded index optical fiber

(Received July 27, 2018; Accepted September 4, 2018; Advance Publication Released Online by J-STAGE September 14, 2018)

Introduction

Recently, liquid-core/liquid-cladding optical waveguides (LLWs), whose concept was firstly introduced by us,1–4 have widely been studied as a key element of optofluidics.5–12 LLWs are usually built using two kinds of miscible liquids that have different refractive indices such as 50% ethanol/water, 5% NaCl aqueous solution/water and etc. Tang et al., on the other hand, proposed an LLW using thermal gradients across homogeneous liquids in microchannels where two streams of water at higher temperature (30 to 80°C) sandwich a stream of water at a lower temperature (21°C),13 based on the phenomenon that the refractive index (RI) of water decreases along with increasing temperature.14

In this work, we tried a different approach to make a LLW using thermal gradients (TG-LLW). That is, the laminar flow of water in a stainless-steel capillary tube was placed in a heat source, and the thermal gradient across the laminar flow was formed to build a LLW. The characteristics of the TG-LLW were studied by both experiments and computational fluid dynamics (CFD) simulations and it was firstly found that the TG-LLW showed the nature of a graded index (GI) optical fiber.

Experimental

The experimental set up of the TG-LLW system is shown in Fig. 1. The laminar flow of water was formed in a stainless-steel capillary tube (i.d., 0.8 mm; o.d., 1.6 mm; 15 cm long) using a HPLC pump, whose flow rate was set from 0 to 9 mL min⁻¹ (the average linear velocity of the flow was 0 to 30 cm s⁻¹). The Reynolds number (Re) of the flow was calculated to be from 0 to ca. 6, which was far smaller than ca. 2000, i.e., the value known to be the upper-limit of Re for laminar flow. Thus, laminar flow should be maintained throughout the experiments. Pure water produced with a Milli-QII system (Millipore, USA) was used throughout this study.

![Fig. 1 Experimental setup of the liquid-core liquid-cladding optical waveguide based on thermal gradients across laminar flow (TG-LLW).](image-url)
The stainless capillary tube was placed in a heat source, i.e., circulated hot water, whose temperature was controlled by a temperature controller (Thermo Regulator CTR-320, IWAKI, Japan), and was changed from room temperature to 70°C. The source light (DPSS laser, 532 nm, Sintec Optronics, China) was introduced through optical fiber (a core-silica clad-plastic optical fiber (o.d., 110 μm), HR-S-FB100, Toray, Japan) and the guided light was monitored through the same out-coupled optical fiber with a Si photodiode (S1337–66BQ, Hamamatsu Photonics, Japan). Then, the photocurrent was measured with a digital electrometer (7451A, ADCMT, Japan). The signal was fed into a personal computer through a GPIB interface. The out-coupled optical fiber was inserted into the stainless capillary tube so as to change the guiding distance; the intensity of the guided light was monitored at each guiding distance (Fig. 1). COMSOL Multiphysics® (Comsol, Sweden) was used for CFD simulation of the temperature distribution in the TG-LLWs.

Results and Discussion

Figure 2 shows the dependence of the guided light intensity upon the temperature of the heat source and the flow rate. As shown in Fig. 2, the higher was the temperature of the heat source, and the greater was the flow rate, the higher was the intensity of the guided light obtained. These results were confirmed by CFD simulation. As shown in Fig. 3a, the increase in the temperature of the heat source resulted in an increase in the thermal gradient in the flow, i.e., an increase in the refractive index (RI) gradients in the flow; the guiding light intensity in the optical fiber is known to increase with an increase in its aperture number, i.e., the RI gradient. Moreover, as shown in Fig. 3b, the CFD simulation also elucidated the effect of the flow rate, i.e., the increase in the flow rate, resulting in an increase in the thermal gradient; the increase of the flow rate decreased the heat efficiently, resulting in a lower temperature of the center region of the flow, while the flow near to the wall stayed equilibrated with its temperature. It should be noted that, as shown in Fig. 2, the guided light intensities at higher flow rates were saturated in the higher temperature range, while they linearly increased at low temperatures. The reason for saturation is unclear at present, because the RI of water linearly decreases with the increase in the temperature region studied. Thus, a linear change in the guiding light intensity should be expected for the whole temperature region studied. This might be caused by intensity fluctuations due to the nature of the LLW as graded-index (GI) optical fiber (see below).

Figure 4 shows the dependence of the guided light intensities upon the guiding distance with various temperatures of the heat source. The guided light intensity changed periodically with the distance, and the period became shorter with increasing temperature of the heat source. Moreover, the period became longer with increasing guiding distance in each temperature, as shown in Fig. 4. This phenomenon is explained by the theory of a graded index (GI) optical fiber. Figure 5 shows a schematic...
diagram of the ray transmission, the temperature profile and the refractive index profile in a GI optical fiber, based on the thermal gradient. It is known that light transmits in GI optical fiber while repeating focusing and defocusing of the guided light as shown in Fig. 5. When \( \Delta \) is defined as
\[
\Delta = \frac{n_2 - n_1}{n_1} \quad (1)
\]
where \( n_1 \) and \( n_2 \) are shown in Fig. 5, the meandering pitch, \( P \), in the GI optical fiber is expressed as
\[
P/2 = \frac{\pi a}{\Delta} \quad (2)
\]
where \( a \) is the radius of the fiber (also see Fig. 5). That is, a smaller refractive index gradient results in a larger value of \( P/2 \).

In the experiments shown in Fig. 4, the guided light intensity increased when the out-coupled optical fiber was in the area of the focusing, but decreased when it was in the area of defocusing. Thus, we obtained the \( P/2 \) values experimentally, as shown in Fig. 4 and Table 1. Moreover, we were also able to calculate the \( P/2 \) values using the refractive index distributions obtained from the simulated temperature distributions in the capillary tube, whose examples are shown in Fig. 3. The calculated \( P/2 \) values are also shown in Table 1. As shown in Table 1, the experimental value and the calculated value were in good agreement with each other, considering the relatively rough estimation of the \( P/2 \) values in both the experiments and the CFD simulation.

Conclusively, the TG-LLW was successfully built with the laminar flow of water in a stainless capillary tube placed in the heat source. Its characteristics were studied with both experiments and CFD simulations, firstly showing that it had the
nature of the GI optical fiber. This TG-LLW may be useful as a long-path cell in various UV-visible spectrometry, especially as an absorbance detector of integrated analytical systems, such as microchip and/or FIA systems. This system can be built with any kinds of materials, such as polymers or glasses, moreover, it can be applied for any kinds of liquid samples, i.e., no limitation in their RI values, which is different from ordinary liquid core waveguide (LCW) applications.\textsuperscript{17–19} The nature of TG-LLW as the GI optical fiber may also be useful to manipulate the light, e.g., focusing and/or defocusing of the guided light in various optofluidic systems in the future.

Acknowledgements

This work was partly supported by a Grant-in-Aid for Scientific Research (No. 23655061) from the Ministry of Education, Culture, Sports, Science and Technology, Japan. The authors thank Prof. P. K. Dasgupta of the University of Texas at Arlington for his important suggestions concerning this work. The authors also thank Prof. K. Miura of Gunma University for his kind instructions concerning the theory of graded-index-optical fiber.

References

1. H. Takiguchi, T. Odake, M. Ozaki, T. Umemura, and K. Tsunoda, \textit{Appl. Spectrosc.}, 2003, 57, 1039.
2. H. Takiguchi, T. Odake, T. Umemura, H. Hotta, and K. Tsunoda, \textit{Anal. Sci.}, 2005, 21, 1269.
3. J. Kamiyama, S. Asanuma, H. Murata, Y. Sugii, H. Hotta, K. Sato, and K. Tsunoda, \textit{Appl. Spectrosc.}, 2013, 67, 1479.
4. H. Takiguchi, S. Asanuma, J. Kamiyama, H. Murata, Y. Hasegawa, S. Yoshizawa, H. Hotta, T. Odake, T. Umemura, K. Sato, and K. Tsunoda, \textit{Anal. Sci.}, 2017, 33, 449.
5. D. B. Wolfe, R. S. Conroy, P. Garstecki, B. T. Mayer, M. A. Fischbach, K. E. Paul, M. Prentiss, and G. M. Whitesides, \textit{Proc. Natl. Acad. Sci. U. S. A.}, 2004, 101, 12434.
6. B. T. Mayer, D. V. Vezenov, V. I. Vullev, and G. M. Whitesides, \textit{Anal. Chem.}, 2005, 77, 1310.
7. X. C. Li, J. Wu, A. Q. Liu, Z. G. Li, Y. C. Soew, H. J. Huang, K. Xu, and J. T. Lin, \textit{Appl. Phys. Lett.}, 2008, 93, 193901.
8. K. S. Lee, S. B. Kim, K. H. Lee, H. J. Sung, and S. S. Kim, \textit{Appl. Phys. Lett.}, 2010, 97, 021109.
9. J. M. Lim, J. P. Urbanski, J. H. Choi, T. Thorsen, and S. M. Yang, \textit{Anal. Chem.}, 2011, 83, 585.
10. X.-D. Fan and I. M. White, \textit{Nat. Photonics}, 2011, 5, 591.
11. K. S. Lee, S. Y. Yoon, K. H. Lee, S. B. Kim, H. J. Sung, and S. S. Kim, \textit{Opt. Express}, 2012, 20, 17348.
12. S.-K. Fan, H.-P. Lee, C.-C. Chien, Y.-W. Lu, Y. Chiu, and F.-Y. Lin, \textit{Lab Chip}, 2016, 16, 847.
13. S. K. Y. Tang, B. T. Mayer, D. V. Vezenov, and G. M. Whitesides, \textit{Appl. Phys. Lett.}, 2006, 88, 061112.
14. R. C. Weast (ed.), in \textit{“CRC Handbook of Chemistry and Physics,”} 61st ed., 1980, CRC, Boca Raton, E-392.
15. H. Kurosawa and M. Yokota, \textit{“FaibaKogaku no Kiso (in Japanese),”} 2002, Oputoronikususha, Tokyo.
16. Y. Suematsu and K. Iga, \textit{“HikariFaibatsushin Nyumon (in Japanese),”} 2006, Ohmu-sha, Tokyo.
17. K. Fuwa, W. Lei, and K. Fujiwara, \textit{Anal. Chem.}, 1984, 56, 1640.
18. P. K. Dasgupta, Z. Genfa, S. K. Poruthoor, S. Caldwell, and S. Dong, \textit{Anal. Chem.}, 1998, 70, 4661.
19. H. Takiguchi, A. Tsubata, M. Miyata, T. Odake, H. Hotta, T. Umemura, and K. Tsunoda, \textit{Anal. Sci.}, 2006, 22, 1017.

| $T_{\text{heating temp.}}$ ($^\circ$C) | 40   | 50   | 60   |
|--------------------------------------|------|------|------|
| Number of $P/2$ cm (Simulation)      | 2.9  | 5.3  | 2.1  |
| $P/2$ cm (Experiment)                | 3.5  | 5.0  | 2.5  |
|                                      | 5.0  | 3.5  | 3.5  |
|                                      | 4.5  | 2.0  | 2.0  |
|                                      | 2.0  | 3.0  | 3.0  |
|                                      | 4.0  |      | 4.0  |
| a. See Fig. 4.                        |      |      |      |

Table 1 Comparison of the meandering pitch ($P/2$) between experiment and CFD simulation.