

NANO-OPTOFLUIDIC WAVEGUIDES WITH SUPER-RESOLUTION LIQUID GAP COUPLING FOR BIOMOLECULAR APPLICATIONS

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ABSTRACT

The evanescent coupling effect between two nano-optofluidic waveguides is demonstrated and studied. The nano-optofluidic waveguides can be easily controlled and tuned by changing the flow rates of the four flow streams such that a nano-gap as small as 50 nm can be easily achieved. The evanescent coupling patterns under different conditions are analyzed to determine the nano-gap and the refractive index contrast of the nano-optofluidic waveguides. Novel and tunable photonic devices can be easily designed and realized by using the nano-optofluidic platform for biomolecular detection and manipulation applications.

KEYWORDS

Nano-optofluidic waveguide, evanescent coupling, biomolecular manipulation

INTRODUCTION

Optofluidics can provide new solutions and opportunities for a wide range of traditional micro-optical components and devices by tuning, reconfiguring, and manipulating small amount of fluids (10^{-9} to 10^{-18} liters). To be specific, with the development of various optofluidic components ranging from microlens [1] and gratings [2] to prisms [3] and waveguides, the hindrance imposed by solid conventional optical components can be easily solved. Recent optofluidic research is focused on the study of light manipulation and the realization of novel photonic characteristics, e.g. an optofluidic waveguide as a transformation optics device, which leads to the first observation of chirped focusing of light and interference in an optofluidic waveguide underpinned by a unique bi-directional GRIN profile in a flow channel [4].

Previously, we have demonstrated the coupling phenomenon between two tunable nano-optofluidic waveguides [5]. In this paper, we further demonstrate how the nano-gap and the refractive index contrast of the nano-optofluidic waveguides can be measured with super-resolution in nanometer by analyzing its resulted evanescent coupling pattern. The nano-optofluidic waveguides can be used for biomolecular manipulation and detection in near future.

THEORETICAL ANALYSIS AND SIMULATION RESULTS

Figure 1 illustrates the design of the two nano-optofluidic waveguides system, which consists of four flow streams. Each optofluidic waveguide is realized by using two flow streams via Dean's flow in a curved microchannel. With the sufficient flow rates (or Péclet number), the inner liquid (red) can be encapsulated by the outer liquid (black). As the two curved microchannels are joined into a straight microchannel downstream, two parallel circular red flow streams with a gap in between are realized. When the refractive index of the red liquid is higher than that of the black liquid, a pair of 3D optical waveguides is formed, such that the gap can be varied by tuning the flow rates of the four flow streams. When the gap is sufficiently small ($< 1 \mu\text{m}$), the light injected in one optofluidic waveguide by the input fiber can be coupled into the other optofluidic waveguide.

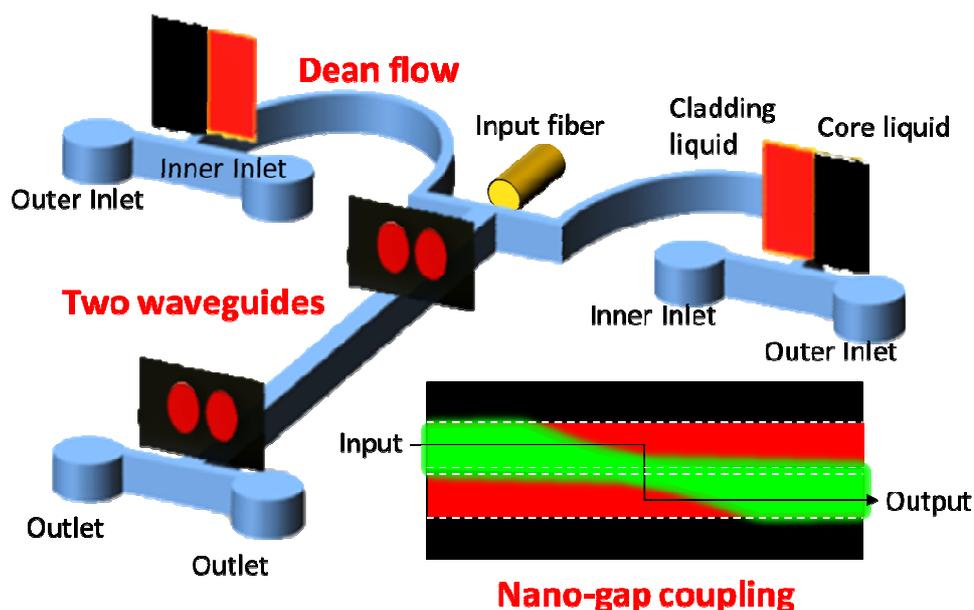


Figure 1: Schematics of the two nano-optofluidic waveguides system tuning by the fluidic flow rates via Dean's flow.

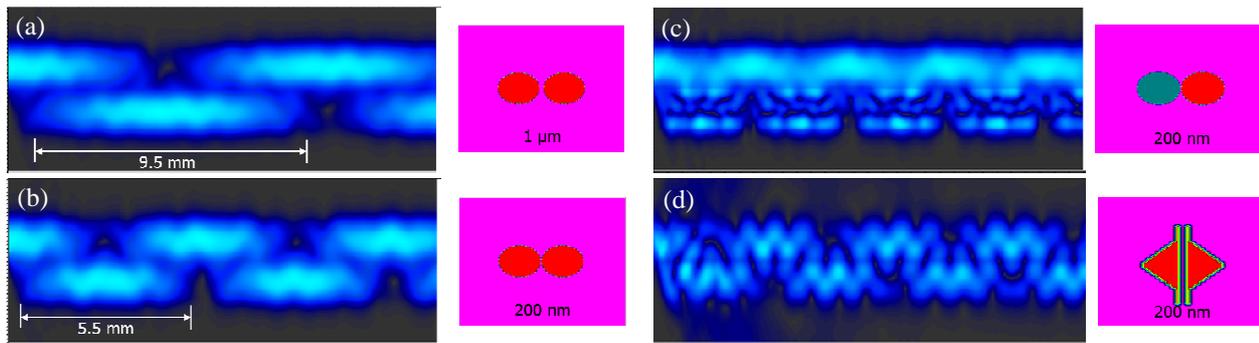


Figure 2: Coupling patterns of the two nano-optofluidic waveguides under different conditions: (a) coupling gap of 1 μm , (b) coupling gap of 200 nm, (c) asymmetrical waveguides with the core refractive index contrast of $\Delta n = 0.001$ and $\Delta n = 0.002$, respectively, and (d) symmetrical waveguides with non-circular cross-sectional profile (a triangular shape profile).

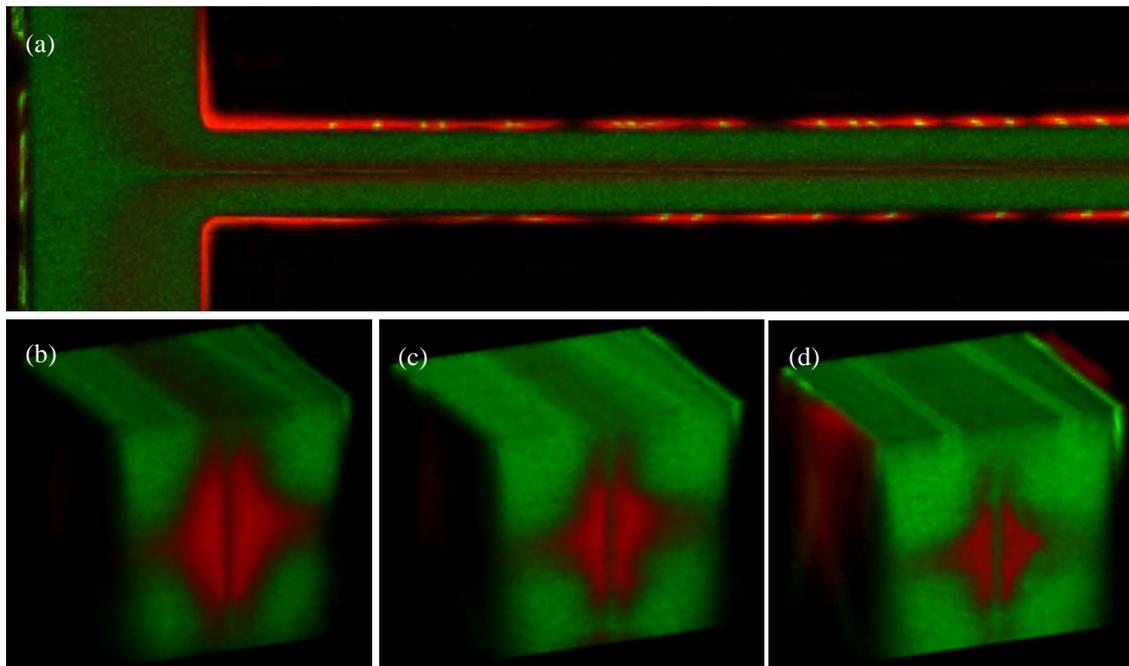


Figure 3: (a) Confocal image which shows the formation of the 3D nano-optofluidic waveguides. The tuning of the nano-gap between the two optofluidic waveguides at different flow rate conditions ($Q_{\text{core}} : Q_{\text{clad}}$) (b) 70 : 70, (c) 53 : 107 and (d) 45 : 135. Unit is $\mu\text{L}/\text{min}$. The measured gaps are (b) 200 nm, (c) 800 nm and (d) 1.4 μm , respectively.

Figure 2 shows the coupling patterns under different conditions. When the gap between the two optofluidic waveguide is decreased from 1- μm to 200 nm, the coupling length is reduced from 9.5 mm to 5.5 mm as shown in Fig. 2(a) and (b). For symmetrical optofluidic waveguide, the coupling pattern is identical between the two optofluidic waveguides. On the contrary, for asymmetrical waveguide, i.e. the core liquids of the two optofluidic waveguides have different contrast (0.001 & 0.002), the coupling pattern is significantly different as shown in Fig. 2(c). For optofluidic waveguide, a triangular cross-sectional fluidic profile is achieved. The coupling pattern of such profile is shown in Fig. 2(d), which is significantly different from the circular one.

EXPERIMENT RESULTS AND DISCUSSIONS

Figure 3 is the confocal images, which show the tuning of the optofluidic waveguides by varying the flow rate of each flow streams. Fig. 3(a) shows the formation of the two optofluidic waveguides after the liquid profile of the flow streams are reshaped by Dean's flow. When the core flow streams and the cladding flow streams have a same flow rate of 70 $\mu\text{L}/\text{min}$ (1 : 1), a measured 200- μm gap is achieved as shown in Fig. 3(b). The cross-sectional image shows that the waveguide has a triangular shape. When the flow rates of the core and cladding flow streams are changed to 53 and 107 $\mu\text{L}/\text{min}$ (1 : 2), respectively, the gap is reduced to 800 nm as shown in Fig. 3(c). The cross-sectional area of the waveguide is reduced at the same time. Subsequently, when the flow rates of two flow streams are changed to 45 and 135 $\mu\text{L}/\text{min}$ (1 : 3), the gap is further reduced to approximately 200 nm as shown in Fig. 3(d).

Figure 4(a-c) shows the coupling patterns of the three flow conditions as illustrated in Fig. 3(b-d). The coupling length is increased when the gap between the optofluidic waveguides is increased, as predicted in the simulation results. Fig. 4(d) shows the comparison between the simulation and experimental results when the flow rate condition of the core and cladding flow streams are fixed at 53 and 107 $\mu\text{L}/\text{min}$, respectively. Both results agree well with each

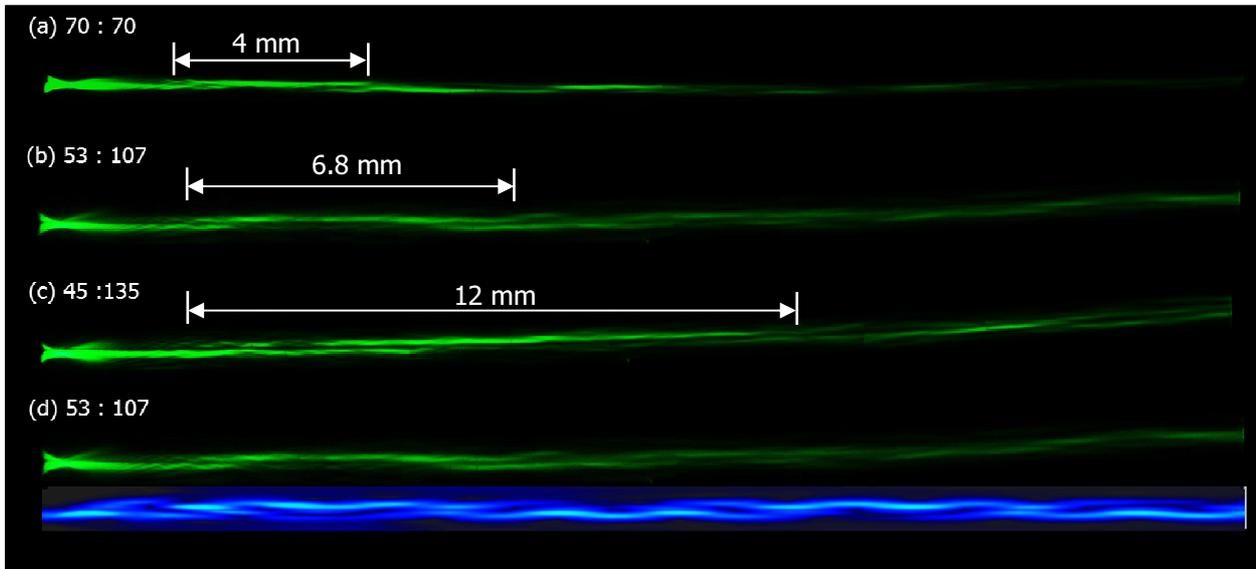


Figure 4: Fluorescent image which shows the coupling patterns of the 3D nano-optofluidic waveguides when the flow rate condition ($Q_{\text{core}} : Q_{\text{clad}}$) is (a) 70 : 70, (b) 53 : 107 and (c) 45 : 135. (d) Comparison between the stimulation and experimental results under the flow rate condition of 53 : 107. Unit is $\mu\text{L}/\text{min}$.

other.

CONCLUSIONS

In conclusion, a 3D optofluidic nano-waveguide coupling system is designed, demonstrated and studied. The nano-optofluidic waveguide is realized by using Dean's flow and can be easily controlled and tuned by changing the flow rates of the four flow streams. The evanescent coupling patterns under different conditions are theoretically simulated and experimentally analyzed to determine the nano-gap and the refractive index contrast of the nano-optofluidic waveguides. With in-depth understanding on the photonic coupling in the nano-waveguide system, novel and tunable photonic devices can be easily designed and realized for biomolecular detection and manipulation applications.

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