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Distinctive Optofluidic Parallel Waveguides

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Abstract

Novel lightwave propagation and bending can be realized in optofluidics by designing the refractive index profile in the microchannel through diffusion via transformation optics. Diffusion in the microfluidic channel is controllable, tunable and reconfigurable, realizing sophisticated bidirectional gradient-index profile for light manipulation. In this paper, 3D optofluidic parallel waveguides are formed using Dean's flow in a microchannel with tunable nano-gap. Photon-tunneling is observed between the optofluidic waveguides, and due to the diffusion process, distinctive light propagation patterns are observed. In symmetrical waveguides, chirped coupling pattern is observed due to the relaxation in index contrast at the downstream. With the ease of changing the composition of the liquids, asymmetrical waveguides can be realized and complex leaky lightwave is observed. The demonstrated optofluidic parallel waveguides will open new doors for more sophisticated and elegant photonic elements such as Eaton lens, designing via transformation optics.

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Keywords: Optofluidics, evanescence wave, near-field optics, transformation optics

1. Introduction

In the last decade, optofluidics, exploiting the synergy between liquids and light, is used to develop tunable and reconfigurable optical elements, such as liquid microlenses [1-2], prisms [3], gratings [4-6], resonators [7] etc. Recently, optofluidic waveguide with bidirectional gradient index profile, designed via transformation optics, is demonstrated to effectively bend and manipulate lightwave in a microfluidic flow [8]. This leads to the possibility in designing sophisticated photonic elements in near-field optics, nano-plasmonics etc.

Here, for the first time, 3D optofluidic parallel waveguides are formed in a microchannel via Dean's flow with its gap in between to be controlled and tuned from 2 μm down to 100 nm. When light is injected in one of the optofluidic waveguide, photon-tunneling to the other waveguide occurs and distinctive chirped coupling length is observed, underpinned by the unique bidirectional refractive index gradient profile in the flow channel. These effects

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are unique in diffusion-induced optofluidic waveguides with high controllability via liquid composition and flow rate conditions.

2. Working principles and chip design

Figure 1 shows the formation of 3D optofluidic parallel waveguides in a microchannel. Each optofluidic waveguide is formed at the upstream by using two flow streams via Dean's flow in a curved microchannel. Under certain flow rates (or Péclet number), the inner liquid can be encapsulated by the outer liquid. When the two curved microchannels are joined into a straight microchannel at the downstream, two parallel circular flow streams with a nano-gap in between is formed. When the refractive index of the core liquid is higher than that of the surrounding 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.

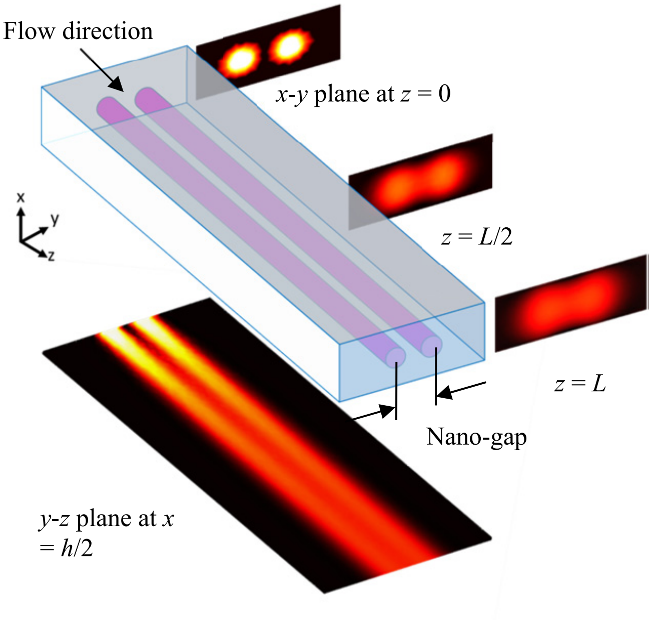
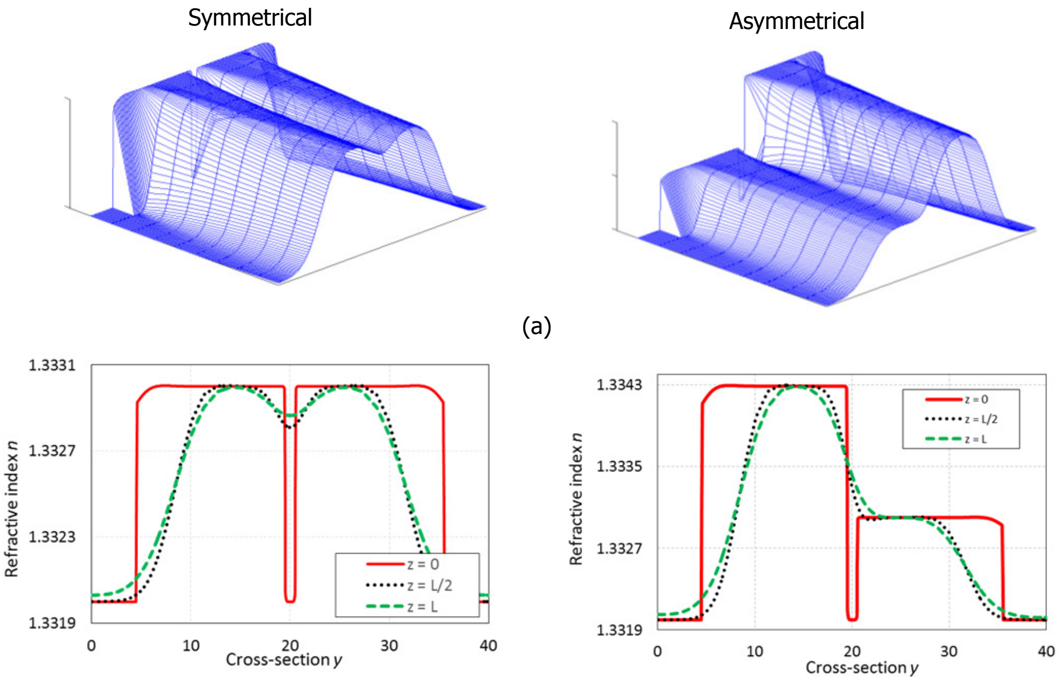


Figure 1: Schematics of optofluidic parallel waveguides in the microchannel. Considering diffusion, the refractive index (concentration) distribution in the microchannel is simulated as shown in different surface planes.

At $z = 0$, the two circular waveguides are distinctive and separated by a nano-gap. When the liquid flow streams are flowing downstream, diffusion occurs whereby its rate is controlled by varying the flow rates of the flow streams. Due to diffusion, the index contrast of the two waveguides relaxes and the two waveguides may merge at the downstream as shown in the surface plane at $z = L$ in Fig. 1. Figure 2a shows the simulated refractive index profile in both the symmetrical and asymmetrical optofluidic parallel waveguides. For symmetrical optofluidic parallel waveguides, both core flow streams have the same refractive index of 1.333 (dilute ethanol-DI water solution), and the surrounding flow stream has a refractive index of 1.332 (pure deionized water). On the other hand, for the asymmetrical optofluidic parallel waveguides, one of the core flow streams is injected with a higher concentration of ethanol-DI water solution to achieve a refractive index of 1.334. Figure 2b illustrates that a step index profile exists across y axis at $z = 0$. This is the initial condition when the waveguides are formed at the upstream. Along the z axis, diffusion occurs and the index contrast relaxes to a gradient index with hyperbolic secant profile. Concurrently, the refractive index in the nano-gap increases gradually, which reduces the index difference between the core and the surrounding flow streams. With this diffusion-induced index profile, the coupling pattern in the optofluidic parallel waveguides is distinctive as compared to its solid equivalent.

3. Experimental results and discussion

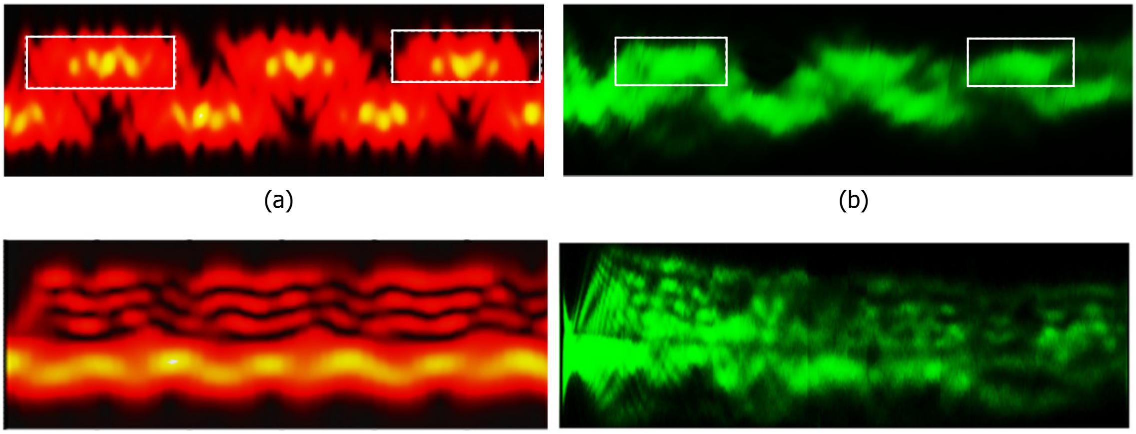
The optofluidic chip is fabricated by polydimethylsiloxane (PDMS) material using standard soft-lithography fabrication techniques. The formation of 3D optofluidic parallel waveguides in the microchannel is not affected by the PDMS material that has a refractive index of 1.412 because the core flow streams are totally encapsulated by the surrounding flow stream. In the experiments, the core flow streams are added with a small amount of Rhodamine 6G. To observe photon-tunneling, a 488-nm laser light is injected into one of the core flow streams by a single mode fiber. Lightwave propagation in the core flow streams can be visualized by exciting the dye solution and detecting the emission using an inverted microscope. Since the microchannel is very long (1 – 2 cm), multiple images are captured by varying the field of view from upstream to downstream to visualize the lightwave propagation in the



(a)

(b)

Figure 2: (a) Simulated refractive index profile at x = h/2 and in symmetrical and asymmetrical waveguides (b) Simulated cross-sectional refractive index profile at z = 0, L/2 and L. For symmetrical waveguides, the core flow streams have a refractive index of 1.333 and the surrounding flow stream has a refractive index of 1.332. For asymmetrical waveguides, one of the core flow stream has a refractive index of 1.334.



(a) (b)

(c) (d)

Figure 3: (a) Simulated and (b) experimental observation of photon-tunneling in a symmetrical waveguides. (c) Simulated and (d) experimental observation of complex leaky lightwave in asymmetrical waveguides.

microchannel. The whole coupling pattern is obtained by combining the series of images using image processing software.

Figure 3a shows the simulated photon-tunneling in the symmetrical optofluidic parallel waveguides. Lightwave is coupled from one to another waveguide, and vice versa. By comparing the coupling pattern with the one in solid waveguides, the coupling length is gradually decreased when light propagates downstream, dominantly caused by the diffusion-induced index contrast relaxation. Figure 3b shows the experimental observation that agrees well with the theoretical analysis. Figure 3(c) and (d) shows the complex leaky lightwave pattern in asymmetrical waveguides in simulation and experiment, which agrees well.

4. Conclusions

In conclusion, optofluidic parallel waveguides in a microchannel are designed and demonstrated. The optofluidic waveguides can be easily reconfigured such as the nano-gap in between by varying flow rate, and transforming from symmetrical to asymmetrical waveguides by changing liquid composition. Due to diffusion, chirped coupling pattern is observed that is different with its solid equivalent. The demonstrated optofluidic parallel waveguides will open new doors for the development of more sophisticated and elegant photonic elements such as Eaton lens, designing via transformation optics.

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